

Notes for Algebraic Structures

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Notes for Algebraic Structures, taught Spring 2016 at Carnegie Mellon University, by Professor Clinton Conley.

Administrativia

◀ Instructor

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◀ Grading

20% HW, $20\% \times 2$ midterms, 40% Final

◀ Homework

Wednesday-Wednesday. Graded for completeness, one starred problem for which no collaboration of any type is allowed.
Most homework out of textbook (“D&F”).

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1. The Integers

◀ Lecture 1 (2016–01–11)

Notation. $\mathbb{N} := \{1, 2, 3, \dots\}$ in this class.

Properties: Order, other things. Least element in a set S : $x \in S$ s.t. $\forall y \in S, x \leq y$
Addition $(\mathbb{Z}, +)$:

- Associativity $(x + y) + z = x + (y + z)$
- Identity $x + 0 = 0 + x = x$
- Inversion $x + (-x) = (-x) + x = 0$
- Commutativity $x + y = y + x$

Multiplication $(\mathbb{Z}, +, \cdot)$:

- Associative
- Distributive
- Identity (“1”)

Integer division: Assume x an integer and $y \in \mathbb{Z}^+$ then $\exists! d \in \mathbb{Z}, \exists! r \in \mathbb{Z} : 0 \leq r < y, x = d \cdot y + r$

Definition 1.1. $y|x$ “ y divides x ” iff $\exists d \in \mathbb{Z} : x = d \cdot y$.

E.g. $3|9, 4 \nmid 7$.

Definition 1.2. d is a GCD of x and y if

- $d|x, d|y$
- If $c|x$ and $c|y$ then $c|d$

◀ Lecture 2 (2016–01–13)

Definition 1.3. Given $a, b \in \mathbb{Z}$, denote by $\mathbb{Z}(a, b)$ the set $\{ax + by | x, y \in \mathbb{Z}\}$.

Theorem 1.4 (Euclid, Bezout). Suppose $a, b \in \mathbb{Z}$ are nonzero and let d be the smallest positive element of $\mathbb{Z}(a, b)$, then d is the unique positive GCD of a and b .

Proof. d is a GCD of a, b

(1) (Existence of positive GCD)

- (a) By integer division, $\exists q \in \mathbb{Z}, \exists r \in \mathbb{Z}$ with $0 \leq r < d$ such that $a = qd + r$. If $r = 0$ then $d|a$, so done. Otherwise, suppose $0 < r < d$, so $r = a - qd$ since $d \in \mathbb{Z}(a, b)$, we may fix x, y st $d = ax + by$, meaning $r = a - q(ax + by) = a(1 - qx) + b(-qy)$, so $r \in \mathbb{Z}(a, b)$, meaning d was not the minimal positive element in $\mathbb{Z}(a, b)$, RAA. Thus, $d|a$
- (b) Homework: If $c|a$ and $c|b$ then $c|(ax + by)$ for all $x, y \in \mathbb{Z}$ Hence $c|d$

- (2) (Uniqueness of positive GCD) Suppose d_1, d_2 are both positive GCDs of a and b . $d_1 | d_2$ and $d_2 | d_1$ as they are both GCDs. i.e., $\exists m, n \in \mathbb{Z}$ such that $d_2 = md_1$ and $d_1 = nd_2$. As $\text{sgn}(d_1) = \text{sgn}(d_2)$, $m \geq 0$ and $n \geq 0$. As $d_1 = mnd_1$, $m = n = 1$. Thus $d_1 = d_2$. □

Definition 1.5. Relatively prime $\iff \gcd(a, b) = 1$

Theorem 1.6. If p is prime, $a, b \in \mathbb{Z}$ are nonzero, and $p | (ab)$, then $p | a$ or $p | b$.

Proof. Consider $d = \gcd(p, a)$. Since $d | p$, we know $d = p$ or $d = 1$.

If $d = p$: By def of GCD, $d | p$ and $d | a$ i.e. $p | p$ and $p | a$ so we're done.

If $d = 1$: Fix integers x and y such that $px + ay = 1$. $b = p(xb) + (ab)y$ as $p | p(xb)$ and $p | \underbrace{(ab)y}_{\uparrow}$, $p | b$. □

Theorem 1.7 (Unique Prime Factorization). Suppose that $a > 1$ an integer, $m, n \geq 1$ and $p_1 \leq p_2 \leq \dots \leq p_m, q_1 \leq q_2 \leq \dots \leq q_n$ are positive primes.

Then $m = n$ and $p_i = q_i$ for all i .

Proof. By induction, it suffices to show $p_1 = q_1$. Suppose not. WLOG, assume $p_1 < q_1$. We know that $p_1 | a$ (as $p_1 | q_1 q_2 \dots q_n$) Hence, $\exists i \leq n$ such that $p_i | q_i$. since p_i and q_i prime, $p_1 = q_i$. However, $p_1 < q_1 \leq q_i = p_1$ so $p_1 < p_2$ contradiction.

Hence $p_1 = q_1$ so by induction, we're done. □

◀ Lecture 3 (2016–01–15)

Teaser: Construct numbers of the form $a + b\sqrt{-5}$ with $a, b \in \mathbb{Z}$.

Notion of addition still exists: (similar to complex numbers, coefficients remain integers)

Same with multiplication

Among these “numbers”, 2 is irreducible. But, 2 is not prime, as $2 \nmid (1 + \sqrt{-5})$ and $2 \nmid (1 + \sqrt{-5})$, but $2 | \underbrace{(1 + \sqrt{-5})(1 - \sqrt{-5})}_{=6=2 \cdot 3}$.

2. The Integers (mod n)

For today, $n > 0$.

Definition 2.1. For $a, b \in \mathbb{Z}$ we say $a \equiv b \pmod{n}$ iff $n \mid (b - a)$.

\equiv is an *equivalence relation*

- Reflexivity: $a \equiv a$
- Symmetry: $a \equiv b \iff b \equiv a$
- Transitivity: $a \equiv b \wedge b \equiv c \implies a \equiv c$

Proof. We know that $a \equiv b$ and $b \equiv c$, i.e. $n \mid (b - a)$ and $n \mid (c - b)$. We want $a \equiv c$, i.e., $n \mid (c - a)$

$$c - a = c + (-b + b) - a = \underbrace{(c - b) + (b - a)}_{n \text{ divides these}}$$

□

Definition 2.2. Denote by \bar{a} or $[a]_n$ the equivalence class of a with respect to $\equiv \pmod{n}$ (I.e., The set $\{b \in \mathbb{Z} : a \equiv b \pmod{n}\} = \{a + kn : k \in \mathbb{Z}\}$).

Example. If $n = 2$, there are 2 equivalence classes:

$$\bar{0} = \{\dots, -4, -2, 0, 2, 4, \dots\} = \bar{2} = \overline{-36}$$

$$\bar{1} = \{\dots, -3, -1, 1, 3, \dots\}$$

Definition 2.3. Denote by $\mathbb{Z}/n\mathbb{Z}$ the collection of all $\equiv \pmod{n}$ equivalence classes.

E.g. $\mathbb{Z}/2\mathbb{Z} = \{\bar{0}, \bar{1}\}$

“Define” addition and multiplication on $\mathbb{Z}/n\mathbb{Z}$ as follows:

$$\begin{aligned}\bar{a} + \bar{b} &= \overline{a + b} \\ \bar{a} \cdot \bar{b} &= \overline{ab}\end{aligned}$$

Makes sense, but we need to check that this definition makes any sense at all (make sure it's *well-defined*). Specifically, we need to make sure that the results of these operations doesn't depend on the representatives of the equivalence classes we chose (e.g. check that $\bar{x} + \bar{z} \equiv \bar{y} + \bar{z}$ if $x \equiv y$).

For brevity, we just show addition.

Theorem 2.4. $+$ and \cdot are well-defined on $\mathbb{Z}/n\mathbb{Z}$

Proof. (of \cdot) Assume that $a_1, a_2, b_1, b_2 \in \mathbb{Z}$ and $a_1 \equiv a_2 \pmod{n}$ and $b_1 \equiv b_2 \pmod{n}$. Then, we want to show that $a_1 b_1 \equiv a_2 b_2 \pmod{n}$.

We know: $n \mid (a_2 - a_1)$ and $n \mid (b_2 - b_1)$.

We want: $n \mid (a_2b_2 - a_1b_1)$.

$$\begin{aligned} a_2b_2 - a_1b_1 &= a_2b_2 + (-a_1b_2 + a_1b_2) - a_1b_1 \\ &= (a_2b_2 - a_1b_2) + (a_1b_2 - a_1b_1) \\ &= \underbrace{(a_2 - a_1)b_2 + a_1(b_2 - b_1)}_{n \text{ divides these}} \end{aligned}$$

So, $n \mid (a_2b_2 - a_1b_1)$ as desired □

Remark: This is a special case of a “quotient construction,” in which you start with a set and an equivalence relation on it and operations on the set that “respect” the equivalence relations (i.e. equivalent inputs yield equivalent outputs)

More notes: Multiplicative inverses are uncommon in the integers (only for 1 and -1). However, it’s “more prevalent” in $\mathbb{Z}/n\mathbb{Z}$ in the following sense:

Theorem 2.5. *Suppose $n > 0$ is an integer, $a \in \mathbb{Z}$ such that $\gcd(n, a) = 1$ (they’re coprime). Then there is $b \in \mathbb{Z}$ such that $ab \equiv 1 \pmod{n}$ (alternatively, $\bar{a} \cdot \bar{b} = \bar{1}$)*

Proof. Use Bézout’s identity (from last lecture) Take integers x, y such that $nx + ay = \gcd(a, n) = 1$. Then, $nx = 1 - ay$, so $n \mid (1 - ay)$, so $1 \equiv ay \pmod{n}$. Choose $b = y$ and we’re done ($\bar{a}\bar{b} \equiv \bar{1}$). □

3. Groups

Definition 3.1. We say that $*$ is a binary operation on some set X if it is a function $*$: $X \times X \rightarrow X$. (That is, $*$ accepts two (ordered) inputs from X and it outputs one element of X .)

Remark: usually write $a * b$ for the output of $*$ on the input (a, b) .

Definition 3.2. A group is a set G with a binary operation $*$ (often abbreviated $(G, *)$) satisfying the following 3 axioms.

- i. Associativity: $\forall a, b, c \in G : (a * b) * c = a * (b * c)$
- ii. Identity: There is some $e \in G$ such that $\forall a \in G : a * e = e * a = a$
- iii. Inversion: $\forall a \in G (\exists b \in G (a * b = b * a = e))$ (where e is as described in ii)

◀ Lecture 4 (2016–01–20)

Recall the definition of a group.

Definition 3.3. $(G, *)$ is an abelian (commutative) group if it is a group and

- iv. $(G, *)$ is commutative ($\forall x, y \in G : x * y = y * x$)

Let $(G, *)$ be an arbitrary but fixed group.

Proposition 3.4. *There is a unique identity element.*

Proof. Suppose e and f both satisfy the second group property. we compute $e * f$ in two ways. $e * f = f$ and $e * f = e$, so by transitivity, $e = f$. □

Proposition 3.5. *If $a \in G$, a has a unique inverse.*

Proof. Suppose that b and c are both inverses for a , $b * a = e$, $a * c = e$. Then,

$$b = b * e = b * (a * c) = (b * a) * c = e * c = c$$

□

Notational Conventions

- We will often just call a group G instead of $(G, *)$
- We abbreviate multiplication $(x * y)$ as $x \cdot y$ or just xy
- We will often write xyz for $(x * y) * z$ (due to associativity)
- When working with $(\mathbb{Z}, +)$, we'll just use $+$
- We'll denote the (unique) identity of G by 1 or by e .
- We'll denote the inverse of x by x^{-1}
- Given an integer exponent $n \in \mathbb{Z}$ and $x \in G$, define

$$x^n = \begin{cases} \prod_{i=1}^n x, & \text{if } n > 0 \\ e, & \text{if } n = 0 \\ \prod_{i=1}^{-n} (x^{-1}), & \text{if } n < 0 \end{cases}$$

Group Examples “Definition:” $\mathbb{Q} = \left\{ \frac{a}{b} : a \in \mathbb{Z}, b \in \mathbb{Z}^+ \right\}$

- (1) $(\mathbb{Z}, +)$ is an abelian group
- (2) (\mathbb{Z}, \times) is not a group
Why? 2 has no inverse in \mathbb{Z} . ($\nexists x \in \mathbb{Z} : (2x = 1)$)
- (3) $(\mathbb{Q}, +)$ is an abelian group
- (4) (\mathbb{Q}, \times) is not a group (0 has no inverse)
- (5) $(\mathbb{Q} \setminus \{0\}, \times)$ is an abelian group.
- (6) $\text{GL}(n)$ is the set of matrices $A_{n \times n}$ for which $\det A_{n \times n} \neq 0$
- (7) The set G of 2×2 matrices with determinant 1, along with matrix multiplication, is a group. Called the “special linear group.”

Closure:

$$\det \left(\begin{pmatrix} a & b \\ c & d \end{pmatrix} \cdot \begin{pmatrix} e & f \\ g & h \end{pmatrix} \right) = (bc - ad)(fg - eh) = 1$$

- i. Associativity: proof left for the reader.
- ii. Identity: $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
- iii. Given $a = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$, take $a^{-1} = \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$, which you can verify is still in G .
The group is *not* abelian. Take $a = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, b = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}$. Verify that $ab \neq ba$.
- (8) Suppose that $X \neq \emptyset$ is some set, and denote by S_X the set of bijections $f : X \rightarrow X$. Then (S_X, \circ) is a group, where \circ is function composition. ($(f \circ g)$ is the function $x \mapsto f(g(x))$.)
Identity is $x \mapsto x$. Inversion $f^{-1} = f^{-1}$.

4. Symmetric Groups

◀ Lecture 5 (2016–01–25)

Recall: if X is a set then S_X is the group of bijections on it.

Definition 4.1. S_X (or Sym_X) is called the symmetric group on X .

Note: \circ is associative because $(f \circ g) \circ h$ is

$$x \xrightarrow{h} (x) \xrightarrow{g} g(h(x)) \xrightarrow{f} f(g(h(x)))$$

Note: if $X = \{1, \dots, n\}$, then we usually write \underline{S}_n instead of $S_{\{1, \dots, n\}}$. (Sometimes called symmetric group of degree n .)

Let's examine S_3 :

| elt. | 1 | 2 | 3 |
|------|---|---|---|
| e | 1 | 2 | 3 |
| a | 1 | 3 | 2 |
| b | 2 | 1 | 3 |
| c | 2 | 3 | 1 |
| d | 3 | 1 | 2 |
| f | 3 | 2 | 1 |

The group has $6 = 3!$ elements.

Lets compute ab and ba

$ab = a \circ b$, looking it up in the table gives $ab = d$ and $ba = c$.

In particular, S_3 is not abelian.

Definition 4.2. A cycle is a permutation σ of the following form:

There is a sequence x_1, x_2, \dots, x_m of finitely many (distinct) elements of $\{1, 2, \dots, n\}$ such that $\sigma(x_{i-1}) = x_i$, $\sigma(x_m) = x_1$, and $\sigma(y) = y$, for $y \notin \{x_1, \dots, x_m\}$.

We call m the length of the cycle.

Ex. In S_3 , $d = \begin{smallmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{smallmatrix}$ is a cycle of length 3, with $x_1 = 1, x_2 = 3, x_3 = 2$.

Ex. In S_3 , $a = \begin{smallmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{smallmatrix}$ is a cycle of length 2, with $x_1 = 2, x_2 = 3$.

Notation. Given a cycle, we can efficiently denote it by $(x_1 x_2 x_3 \dots x_m)$.

Example. In S_3 , $a = \begin{smallmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{smallmatrix}$ would be written as $(1 \ 3 \ 2)$.

Let's work in S_5 .

$\varphi := \begin{smallmatrix} 1 & 2 & 3 & 4 & 5 \\ 3 & 4 & 1 & 5 & 2 \end{smallmatrix}$ is not a cycle, but it is the “superposition” of two cycles $(1 \ 3)$ and $(2 \ 4 \ 5)$. Thus, we may write $\varphi = (1 \ 3) \circ (2 \ 4 \ 5)$, or $(2 \ 4 \ 5)(1 \ 3)$.

Theorem 4.3. Every permutation in S_n may be written as the product of “disjoint” cycles. (The identity is the empty product).

Proof. Sketch: If you have e then you're done trivially.

Otherwise, fix the least element x of $\{1, \dots, n\}$ “moved” by σ (i.e. $\sigma(x) \neq x$). Look at $x, \sigma(x), \sigma^2(x), \dots, \sigma^m(x) = \sigma^n(x)$, $n < m$. So, as σ is invertible, $\sigma^{m-n}(x) = x$, so x is part of a cycle. \square

Theorem 4.4. *Cycles can be written as a product of transpositions.*

General propositions on inversion in groups

Let G be a group, and let $a, b, x \in G$ be arbitrary.

- $(a^{-1})^{-1} = a$

Proof. Show that a is the inverse of a^{-1} . Follows from group axiom. \square

- $(ab)^{-1} = b^{-1}a^{-1}$

Proof. $(ab)(b^{-1}a^{-1}) = (a(bb^{-1}))a^{-1} = (ae)a^{-1} = aa^{-1} = e$. Similarly, this works when we multiply from the other side. \square

◀ Lecture 6 (2016–01–27)

Definition 4.5. The cardinality (or order) of a group G is the number of elements in it, denoted by $|G|$.

Example.

- $|\mathbb{Z}| = \infty (= \aleph_0)$
- $|\mathbb{Z}/5\mathbb{Z}| = 5$
- $|S_4| = 4! = 24$

Definition 4.6. Given a group G and $x \in G$, the order of x is the smallest integer $n > 0$ such that $x^n = e$. If no such n exists, we say the order is ∞ .

We denote by $|x|$ the order of x .

Example. In $(\mathbb{Z}, +)$: $|0| = 1$, $|5| = \infty$.

In S_5 : $|(1\ 3)| = 2$, $|(2\ 4\ 5)| = 3$, $|(1\ 3)(2\ 4\ 5)| = 6$.

Proposition 4.7. *If G is a finite group, every $x \in G$ has finite order. Moreover, $|x| \leq |G|$.*

Proof. Say $|G| = k$. Consider the sequence $x^0, x^1, x^2, \dots, x^k$. There are $k + 1$ items in the sequence. So $\exists m < n$ such that $x^m = x^n$. $x^{n-m} = x^n x^{-m} = x^m x^{-m} = e$. As $0 < n - m \leq k$, it follows that $|x| \leq n - m \leq |G|$. \square

5. Subgroups

Definition 5.1. Suppose $(G, *)$ is a group and $H \subseteq G$ some subset of G . We say H is a subgroup of G , written $H \leq G$ if $(H, *)$ happens to be a group, i.e., the following properties hold:

$*$ is a associative binary operator on H (i.e., it's closed) with inverses and an identity element.

Example.

- $\mathbb{Z} \leq \mathbb{Q}$ (under addition)
- Even integers $\leq \mathbb{Z}$ (under addition)
- $n\mathbb{Z} \leq \mathbb{Z}$, where $n\mathbb{Z} := \{nx : x \in \mathbb{Z}\}$
 Aside: every subgroup of \mathbb{Z} is of the form $n\mathbb{Z}$
- $\{e, (1\ 2)(3\ 4), (1\ 3)(2\ 4), (1\ 4)(2\ 3)\} \leq S_4$.

Proposition 5.2. (*Homework*): $H \leq G$ iff

- (a) $H \neq \emptyset$ (*nonempty*)
- (b) $\forall x, y \in H (xy \in H)$ (*closed under product*)
- (c) $\forall x \in H (x^{-1} \in H)$ (*closed under inverses*)

Proposition 5.3. Suppose G is a finite group. Then $H \leq G$ iff $H \neq \emptyset$ and $\forall x, y \in H : xy \in H$.

Proof. We show that for $H \subseteq G$ (a) and (b) \implies (c) (letters from proposition (5.2))
 Fix $x \in H$. Since G is finite, $|x|$ is finite (in G). Say $|x| = n > 0$ $x^n = \underbrace{x \cdot x \cdot \dots \cdot x}_{n \text{ times}} = e_G$.

Hence, $e_G \in H$.

Examine x^{n-1} .

$$x^{n-1} = \begin{cases} x^0 = e & \text{if } n = 1 \\ \underbrace{x \cdot x \cdot \dots \cdot x}_{n \text{ times}} & \text{if } n > 1 \end{cases}$$

But $x^{n-1} = x^{-1}$, since $x^{n-1}x = x^n = e$. Thus, (c) holds for H . □

Remark. $\mathbb{N} = \{0, 1, \dots\} \subseteq \mathbb{Z}$, but $\mathbb{N} \not\leq \mathbb{Z}$, despite satisfying (a) and (b).

6. (Left) Coset equivalence

Suppose G is a group and $H \leq G$ is a subgroup of G .

Definition 6.1. We say $x \sim y \pmod{H}$ if $x^{-1}y \in H$.

Proposition 6.2. $\sim \pmod{H}$ is an equivalence relation.

Proof.

- Reflexivity ($x \sim x$):

$x^{-1}x = e \in H$, so $x \sim x$.

- Symmetry ($x \sim y \implies y \sim x$):

We know $x^{-1}y \in H$. H is closed under inversion, so $H \ni (x^{-1}y)^{-1} = (y^{-1}(x^{-1})^{-1}) = (y^{-1}x)$. Thus, $y \sim x$.

- Transitivity ($(x \sim y) \wedge (y \sim z) \implies (x \sim z)$):

We know $x^{-1}y \in H$ and $y^{-1}z \in H$.

Thus, $H \ni (x^{-1}y)(y^{-1}z) = x^{-1}ez = x^{-1}z$, so $x \sim z$.

□

◀ Lecture 7 (2016–01–29)

G is a group. $H \leq G$ a fixed subgroup of G .

Given $x, y \in G$, $x \sim y \pmod{H}$ iff

$$x^{-1}y \in H.$$

Last time: we showed it was an equivalence relation.

What are the equivalence classes of $\sim \pmod{H}$? We examine

$$\begin{aligned} [x] &= \{y \in G : x \sim y \pmod{H}\} \\ &= \{y \in G : x^{-1}y \in H\} \\ &= \{y \in G : \exists h \in H (x^{-1}y = h)\} \\ &= \{y \in G : \exists h \in H (x(x^{-1}y) = xh)\} \\ &= \{y \in G : \exists h \in H (y = xh)\} \end{aligned}$$

So, $[x]$ is exactly the set

$$\{xh : h \in H\}.$$

Notation. We write xH to abbreviate the set $\{xh : h \in H\}$.

Definition 6.3. The equivalence class xH is called the (left) coset of x with respect to H .

Notation. The cyclic subgroup of x is denoted by $\langle x \rangle$.

Examples:

- $G = (\mathbb{Z}, +)$, $H = n\mathbb{Z} = \text{multiples of } n$. So $H \leq G$. For $x \in \mathbb{Z}$, its coset is $\bar{x} = \{x + h : h \in n\mathbb{Z}\} = \{x + nk : k \in \mathbb{Z}\}$
- $G = S_3 = \{e, (1\ 2), (1\ 3), (2\ 3), (1\ 2\ 3), (1\ 3\ 2)\}$ Take $H = \{e, (1\ 2\ 3), (1\ 3\ 2)\} \leq S_3$ (the cyclic subgroup of $(1\ 2\ 3)$).

So what are the cosets? $eH = \{eh : h \in H\} = \{h : h \in H\} = H$. (In general, eH is always just H). (Even more generally, $xH = H$ whenever $x \in H$.)

Another coset is $(1\ 2)H$. Just compute $(1\ 2)h$ for each $h \in H$. Thus

$$(1\ 2)H = \left\{ \begin{array}{lll} (1\ 2) & e & = (1\ 2) \\ (1\ 2) & (1\ 2\ 3) & = (2\ 3) \\ (1\ 2) & (1\ 3\ 2) & = (1\ 3) \end{array} \right\} = \{(1\ 2), (2\ 3), (1\ 3)\}$$

We note that $(1\ 2)H = (2\ 3)H = (1\ 3)H$, as each of those are in $(1\ 2)H$.

- $G = S_3$, $K = \langle (1\ 3) \rangle = \{e, (1\ 3)\} \leq G$. Analyze cosets mod K .

Easy coset: $eK = K$.

For the next coset, choose $(1\ 2\ 3)K$

$$(1\ 2\ 3)K = \left\{ \begin{array}{lll} (1\ 2\ 3) & e & = (1\ 2\ 3) \\ (1\ 2\ 3) & (1\ 3) & = (2\ 3) \end{array} \right\} = \{(1\ 2\ 3), (2\ 3)\}$$

Next coset after that is $(1\ 2)K = \{(1\ 2), (1\ 3\ 2)\}$.

We note that the equivalence classes mod K partition S_3 , Although they are not all subgroups.

In the last two examples, it wasn't a coincidence that each coset was of the same cardinality.

Proposition 6.4. *Suppose G is a group, $H \leq G$, and $x \in G$. Then $|xH| = |H|$.*

Proof. We establish a bijection between H and xH .

Define $\varphi : H \rightarrow xH$, $\varphi(h) = xh$.

Claim (1). φ is surjective.

Proof. Suppose $y \in xH$.

By definition of xH , $\exists h \in H$ such that $y = xh$. So, $y = \varphi(h)$. □(C1)

Claim (2). φ is injective.

Proof. Suppose $h_1, h_2 \in H$ such that $\varphi(h_1) = \varphi(h_2)$.

By definition of φ , we have $xh_1 = xh_2$. Since G is a group, x has an inverse x^{-1} .

Thus, $x^{-1}(xh_1) = x^{-1}(xh_2) \implies h_1 = h_2$ as desired. □(C2)

Thus φ is a bijection, meaning $|xH| = |H|$ as desired. □(Prop.)

Theorem 6.5 (Lagrange's Theorem). *Suppose that G is a finite group and $H \leq G$. Then $|H|$ divides $|G|$.*

Proof. Left coset equivalence partitions G into k equivalence classes of size $|H|$.

Thus $|G| = k|H|$, as desired. □

Corollary 6.5.1. *Suppose that G is a finite group and $x \in G$. Then $|x|$ divides $|G|$.*

Proof. Consider $\langle x \rangle$ (the cyclic subgroup generated by x). $\langle x \rangle = \{e, x, x^2, \dots, x^{n-1}\}$, where $|x| = n$. $|\langle x \rangle| = n$. Hence $n = |x|$ divides $|G|$. □

◀ Lecture 8 (2016–02–01)

We go to the previous lecture for examples.

Consider $G = S_3$, $H = \{e, (1\ 2\ 3), (1\ 3\ 2)\} \leq G$, $K = \langle (1\ 3) \rangle = \{e, (1\ 3)\} \leq G$.

Definition 6.6. If G is a group and $H \leq G$, denote by G/H (G “mod” H) the collection of (left) cosets of H in G .

Example.

(a) $n\mathbb{Z} \leq \mathbb{Z}$, $\mathbb{Z}/n\mathbb{Z} = \{\overline{0}, \overline{1}, \dots, \overline{n-1}\}$

(b) $S_3/H = \{eH, (1\ 2)H\}$, $eH = H$, $(1\ 2)H = \{(1\ 2), (2\ 3), (1\ 3)\}$

(c) $S_3/K = \{\{e, (1\ 3)\}, \{(1\ 2\ 3), 23\}, \{(1\ 2), (1\ 3\ 2)\}\}$

7. Normal Subgroups

Fundamental question: When is there “natural” group operation on G/H ? Prototype: $\mathbb{Z}/n\mathbb{Z}$, $\overline{x} + \overline{y} = \overline{x + y}$.

Natural Attempt:

$$(g_1H)(g_2(H)) \stackrel{?}{=} (g_1g_2)H.$$

This works fine for (b) in the sense that if $g_1H = g_2H$ and $k_1H = k_2H$ then $(g_1k_1)H = (g_2k_2)H$ (verification left to reader).

But it *doesn't* work for (c). e and $(1\ 3)$ both represent eK . But they give *different* cosets after multiplication by $(1\ 2\ 3)$.

- $e(1\ 2\ 3) = (1\ 2\ 3)$
- $(1\ 3)(1\ 2\ 3) = (1\ 2)$.

In general, what would we need to have, in order to have multiplication in G/H be “well-defined?”

We want: $\underbrace{x_1 \sim x_2}_{x_1^{-1}x_2=h \in H}$ and $\underbrace{y_1 \sim y_2}_{y_1^{-1}y_2=k \in H} \implies x_1y_1 \sim x_2y_2$. Thus, we want $(x_1y_1)^{-1}(x_2y_2) \in H$.

$$(x_1y_1)^{-1}(x_2y_2) = (y_1^{-1}x_1^{-1})(x_2y_2) = y_1^{-1}(x_1^{-1}x_2)y_1k = \underbrace{y_1^{-1}hy_1}_{\in H} \underbrace{k}_{\in H} \in H$$

This expression motivates the definition of a normal subgroup

Definition 7.1. If G is a group, and $N \leq G$, we say N is normal if for all $n \in N$, and $g \in G$, we have $g^{-1}ng \in N$. We write this as $N \trianglelefteq G$.

Remark. For fixed $g \in G$, the map for $x \in G$

$$x \mapsto g^{-1}xg$$

is called conjugation by g .

Thus, N is normal if it is stable under all conjugation.

Theorem 7.2. Let G a group $H \leq G$. Then the following are equivalent:

- (I) $(g_1H)(g_2H) = (g_1g_2)H$ is a well-defined group operation on G/H .
- (II) $H \trianglelefteq G$.

(II) \implies (I). $x_1^{-1}x_2 = h, y_1^{-1}y_2 = k$. (Exercise for the reader) □

(I) \implies (II). Suppose $h \in H$ and $g \in H$ want $g^{-1}hg \in H$.

Note: $e \sim h$ since $e^{-1}h = h \in H$.

By (I), we have $(eg)H = (eH)(gH) = (hH)(gH) = (hg)H$.

So, $gH = (hg)H$, meaning $g \sim hg$, so $g^{-1}hg \in H$. □(Thm)

Proposition 7.3. If G is abelian, every subgroup is normal.

Proof. Fix $H \leq G$, $h \in H$, $g \in G$. Then $g^{-1}hg = g^{-1}gh = h \in H$. □

Proposition 7.4. $G \trianglelefteq G$ and $\{e\} \trianglelefteq G$.

Proof. $g^{-1}hg \in G$ and $g^{-1}eg = g^{-1}g = e \in \{e\}$. □

Definition 7.5. For $A \subseteq G$, denote by $g^{-1}Ag$ the set $\{g^{-1}ag : a \in A\}$.
Called the conjugate of A by G .

Remark. Thus, N is normal iff $N \leq G$ and $\forall g \in G : g^{-1}Ng \subseteq N$.

Proposition 7.6. $N \trianglelefteq G \implies \forall g \in G : g^{-1}Ng = N$

Proof. Fix $n \in N$. we want $n \in g^{-1}Ng$. (This shows $N \subseteq g^{-1}Ng$.)
We know by $N \trianglelefteq G$ that $m = (g^{-1})^{-1}n(g^{-1}) \in N$. Then $m = gng^{-1}$.

Claim. $g^{-1}mg = n$

Proof. $g^{-1}(gng^{-1})g = \cancel{(g^{-1}g)}n\cancel{(g^{-1}g)} = n$

□(Claim)

□(Prop)

8. Homomorphisms

Definition 8.1. Suppose G, H are groups and $\varphi : G \rightarrow H$ is a function. We say φ is a homomorphism if $\forall g_1, g_2 \in G : \varphi(g_1 *_{\mathcal{G}} g_2) = \varphi(g_1) *_H \varphi(g_2)$.

Definition 8.2. Suppose $\varphi : G \rightarrow H$ is a homomorphism. The Kernel of ϕ is $\text{Ker}(\varphi) = \{g \in G : \varphi(g) = e_H\} = \varphi^{-1}(\{e_H\})$.

Proposition 8.3. Suppose $\varphi : G \rightarrow H$ is a homomorphism between groups. Then $K = \text{Ker}(\varphi) \trianglelefteq G$.

Proof.

Claim (1). $K \neq \emptyset$. In fact, $e_G \in K$.

Proof. We know that e_G is the unique element of G such that $\forall g \in G (e_G g = g e_g = g)$.

So, $\varphi(e_G) = \varphi(e_G e_G) = \varphi(e_G) \varphi(e_G) = \varphi(e_G)$ Multiplying both sides by $\varphi(e_G)^{-1} \in H$

So $\varphi(e_G) = e_H$. $\square(\text{C1})$

Claim (2). $\forall g \in G \varphi(g^{-1}) = (\varphi(g))^{-1}$

Proof. $\varphi(g^{-1})\varphi(g) = \varphi(gg^{-1}) = \varphi(e_G) = e_H$ By symmetry, $\varphi(g)\varphi(g^{-1}) = e_H$ $\square(\text{C2})$

$\square(\text{Prop.})$

◀ Lecture 9 (2016–02–03)

Class Note

Midterm 1 is on Friday February 26th (in class)

Last time: showed that the kernel of a homomorphism is a subgroup.

Proposition 8.4. $K \trianglelefteq G$.

Proof. First we show $K \leq G$.

- $K \neq \emptyset$ as $e_G \in K$.
- $\forall g_1, g_2 \in K, g_1 g_2 \in K$:
 $\varphi(g_1 g_2) = \varphi(g_1) \varphi(g_2) = e_H e_H = e_H$ So $g_1 g_2 \in K$
- $\forall g \in K, g^{-1} \in K$:
 $\varphi(g^{-1}) = (\varphi(g))^{-1} = e_H^{-1} = e_H$
 So $g^{-1} \in K$

Thus, $K \leq G$. Next, we prove. $\forall k \in K, \forall g \in G$:

$$\varphi(g^{-1}kg) = \varphi(g^{-1})\varphi(h)\varphi(g) = (\varphi(g))^{-1}e_H\varphi(g) = e_H$$

Hence $g^{-1}kg \in K$. \square

Definition 8.5. If $\varphi : G \rightarrow H$ is a group homomorphism, and $h \in H$, the fiber above h is the set $\varphi^{-1}(\{h\})$.

Thus, $\text{Ker}(\varphi)$ is the fiber above e_H .

Example.

- $\varphi(\mathbb{R}, +) \rightarrow (\mathbb{R}^+, \times)$, $\varphi(r) = e^r$ φ is a homomorphism since $\varphi(r+s) = e^{r+s} = e^r e^s = \varphi(r) \times \varphi(s)$
 $\text{Ker}(\varphi) = \{r \in \mathbb{R} : \varphi(r) = 1\} = \{0\}$.
 The fiber above $s \in \mathbb{R}^+$: $\varphi(r) = s \iff e^r = s \iff r = \ln s$. Thus $\varphi^{-1}(\{s\}) = \{\ln s\}$.
- $\varphi : (\mathbb{C} \setminus \{0\}, \times) \rightarrow (\mathbb{R} \setminus \{0\}, \times)$, $\varphi(a+bi) = a^2 + b^2$.
 φ is a homomorphism (verification left to the reader).
 $\text{Ker}(\varphi) = \{a+bi : \varphi(a+bi) = 1\} = \{a+bi : a^2 + b^2 = 1\}$, which is the unit circle in the complex plane.
 Fix $r \in \mathbb{R} \setminus \{0\}$, let's examine the fiber above r :

$$\{a+bi : a^2 + b^2 = r\} = \begin{cases} \emptyset & \text{if } r < 0 \\ \text{Circle of radius } \sqrt{r} & \text{if } r > 0 \end{cases}$$

- Start with a group G , normal $N \trianglelefteq G$. $\varphi : G \rightarrow G/N$, $\varphi(g) = gN$ is a homomorphism.

Proof. $\varphi(g_1 g_2) = (g_1 g_2)N = (g_1 N)(g_2 N) = \varphi(g_1) \varphi(g_2)$ □

$$\text{Ker}(\varphi) = \{g : \varphi(g) = eN\} = \{g : \varphi(g) = eN\} = N.$$

This leads us to the realization that:

Proposition 8.6. $N \trianglelefteq G \iff N = \text{Ker}(\phi)$ for some homomorphism $\varphi : G \rightarrow H$, for any group H .

Why do all fibers look alike?

Proposition 8.7. If $\phi : G \rightarrow H$ is a group homomorphism and $h \in H$, then $\varphi^{-1}(\{h\})$ is either \emptyset or gK for some $g \in G$, where $K = \text{Ker}(\varphi)$

Proof. If $\nexists g \in G$ such that $\varphi(g) = h$ then $\varphi^{-1}(\{h\}) = \emptyset$.

Else, fix some $g \in G$ such that $\varphi(g) = h$.

Claim (1). $gK \supseteq \varphi^{-1}(\{h\})$

Proof. Suppose $g' \in \varphi^{-1}(\{h\})$ (i.e. $\varphi(g') = h$). Want $g' \in gK$. So, $\varphi(gg'^{-1}) = \varphi(g)\varphi(g'^{-1}) = \varphi(g)\varphi(g')^{-1} = hh^{-1} = e_H$. Hence $gg'^{-1} \in K$, so $g' \sim g \pmod{K}$, so $g' \in gK$. □(C1)

Claim (2). $gK \subseteq \varphi^{-1}(\{h\})$

Proof. Suppose $g' \in gK$, want $\varphi(g') = h$. Fix $k \in K$ such that $g' = gk$. $\varphi(g') = \varphi(gk) = \varphi(g)\varphi(k) = he_H = h$. □(C2)

Thus, $gK = \varphi^{-1}(\{h\})$, as desired. □(Prop.)

Corollary 8.7.1. If $\varphi : G \rightarrow H$ is a group homomorphism, the following are equal:

- φ is injective.
- $\text{Ker}(\varphi) = \{e_G\}$

Definition 8.8. A map $\varphi : G \rightarrow H$ between groups is an isomorphism if it is a bijective homomorphism. We often say $G \cong H$ if there exists an isomorphism $\phi : G \rightarrow H$.

Intuition: Isomorphic groups have the “same operation” on different sets.

Example. Let $G = \{a, b\}$ $\begin{array}{c|cc} & a & b \\ a & a & b \\ b & b & a \end{array}$ Then, $G \cong \mathbb{Z}/2\mathbb{Z}$ via $\varphi : a \mapsto \bar{0}, b \mapsto \bar{1}$

We know $\varphi : G \rightarrow H$ is an isomorphism if it's a homomorphism, surjective, and $\text{Ker}(\varphi) = \{e_G\}$.

◀ Lecture 10 (2016–02–06)

Definition 8.9. If $\varphi : G \rightarrow H$ is a function, denote by $\text{Im}(\varphi)$, or $\varphi(G)$, or $\varphi[G]$ the image of G , i.e., the set $\{h \in H, \exists g \in G : \varphi(g) = h\}$.

Exercise. Prove: If $\varphi : G \rightarrow H$ is a group homomorphism then $\varphi[G] \leq H$.

Theorem 8.10 (First Isomorphism Theorem). *If $\varphi : G \rightarrow H$ is a group homomorphism, then $\varphi[G] \cong G/\text{Ker}(\varphi)$.*

Proof. Abbreviate $I := \varphi[G], K := \text{Ker}(\varphi)$. We know for $h \in I$: $\varphi^{-1}(\{h\}) \neq \emptyset$. Hence, $\varphi^{-1}(\{h\}) = gK$ for some $gK \in G/K$. Then, define $\psi : I \rightarrow G/K$. $\psi(h) = \varphi^{-1}(\{h\}) = gK$.

Claim. $\psi : I \rightarrow G/K$ is a group isomorphism.

Proof. We show that ψ is a bijective homomorphism in three parts:

(a) ψ is a homomorphism:

Fix $h_1, h_2 \in I$, want $\psi(h_1, h_2) = \psi(h_1)\psi(h_2)$. Fix g_1, g_2 such that $\varphi(g_1) = h_1, \varphi(g_2) = h_2$. Then $\varphi(g_1g_2) = h_1h_2$ by def of homomorphism. So, $\psi(h_1h_2) = g_1g_2K = (g_1K)(g_2K) = \psi(h_1)\psi(h_2)$. $\square(a)$

(b) ψ is a surjection:

Fix $gK \in G/K$. Want $h \in I$ with $\psi(h) = gK$. Want $h \in I$ with $\psi(h) = gK$. Choose $h \in \psi(g)$. Then by def, $g \in \varphi^{-1}(\{h\})$. Thus, $\psi(h) = \varphi^{-1}(\{h\}) = gK$. $\square(b)$

(c) ψ is an injection:

As remarked, it suffices to show

$$\text{Ker}(\psi) = \{h \in I : \psi(h) = \underbrace{e_G K}_{=e_{G/K}}\} = \{h \in I : \varphi^{-1}(\{h\})\} = \{h \in I : \varphi(e_G) = h\} = \{e_H\}$$

$\square(c)$

$\square(\text{Claim})$

$\square(\text{Thm})$

Definition 8.11. A group G is cyclic if $\exists x \in G : \langle x \rangle = G$. (Where $\langle x \rangle = \{x^n : n \in \mathbb{Z}\}$.)

Proposition 8.12. *If G is a cyclic group, then $G \cong \mathbb{Z}$, or $G \cong (\mathbb{Z}/n\mathbb{Z})$ for some $n \in \mathbb{Z}$.*

Proof. As G is cyclic, take $x \in G$ such that $\langle x \rangle = G$. the map $\varphi : (\mathbb{Z}, +) \rightarrow G, \varphi(n) = x^n$. By hypothesis, $\langle x \rangle = G$. φ is surjective, so $\text{Im}(\varphi) = G$. By first isomorphism theorem, $G \cong (\mathbb{Z}/\text{Ker}(\varphi))$.

Assume $\nexists n > 0$ such that $x^n = 1_G$ (i.e., the order of x in G is infinite.) Then $\text{Ker}(\varphi) = \{n \cdot x^n = e_G\} = \{0\}$. Also $\mathbb{Z}/\{0\} \cong \mathbb{Z}$ (proof left as exercise). Thus, $G \cong \mathbb{Z}$.

Otherwise, fix the least $n > 0$ such that $x^n = e_G$ (so $n = |x|$).

Check (exercise): $\text{Ker}(\varphi) = \{m \in \mathbb{Z} : x^m = e_G\} = n\mathbb{Z}$. Thus $G \cong \mathbb{Z}/\text{Ker}(\varphi) = \mathbb{Z}/n\mathbb{Z}$. \square

Corollary 8.12.1. *Suppose $p > 1$ is prime and G is a group with $|G| = p$. Then $G \cong (\mathbb{Z}/p\mathbb{Z})$.*

Proof. Fix any $x \in G$, $x \neq e^G$. $|x| \neq 1$. Additionally $|x|$ divides $|G|$. Thus $|x| = p$, as p is prime. Then $\langle x \rangle = G$. \square

Our next big motivational question: Given $n \in \mathbb{N}$, can we “classify” (or list) all groups of cardinality n (up to \cong)?

What we know so far:

| n | Groups: |
|-----|----------------------------------|
| 0 | None |
| 1 | $\{e\}$ |
| 2 | $\mathbb{Z}/2\mathbb{Z}$ |
| 3 | $\mathbb{Z}/3\mathbb{Z}$ |
| 4 | $\mathbb{Z}/4\mathbb{Z}, \dots?$ |
| 5 | $\mathbb{Z}/5\mathbb{Z}$ |
| 6 | $\mathbb{Z}/6\mathbb{Z}, \dots?$ |

Definition 8.13. G, H are groups, build a group of the direct product of G and H , denoted $G \times H$ with underlying set $\{(g, h) : g \in G, h \in H\}$, and group operation $(g_1, h_1) \cdot (g_2, h_2) = ((g_1 \cdot_G g_2), (h_1 \cdot_H h_2))$

Proposition 8.14. *If $|G| = 2$ then $G \cong \mathbb{Z}/4\mathbb{Z}$ or $G \cong ((\mathbb{Z}/2\mathbb{Z}) \times (\mathbb{Z}/2\mathbb{Z}))$*

◀ **Lecture 11 (2016–02–08)**

Proposition 8.15. *Suppose G is a group. Then $G/\{e_G\} \cong G$ and $G/G \cong \{e_G\}$.*

Proof. Consider the homomorphism $\varphi : G \rightarrow G$ with $\varphi(g) = g$. $\text{Ker}(\varphi) = \{g \in G : \varphi(g) = e_G\} = \{e_G\}$, and $\varphi[G] = G$.

Thus, the first isomorphism theorem states that $G/\text{Ker}(\varphi) \cong \varphi[G]$.

Next, consider the homomorphism $\psi : G \rightarrow G$, $\psi(g) = e_G$. Then $\text{Ker}(\psi) = G$, $\text{Im}(\psi) = \{e_G\}$. By the first isomorphism theorem, $G/G \cong \{e_G\}$. \square

Groups of cardinality 4

Proposition 8.16. *If G is a group with $|G| = 4$ then $G \cong \mathbb{Z}/4\mathbb{Z}$ or $G \cong (\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z})$.*

We note that the above groups are not isomorphic because there is no element of order 4 in $(\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z})$.

Proof. Possible orders for elements are 1, 2, or 4.

Two cases:

- (1) $\exists g \in G, |g| = 4$ then $G = \langle g \rangle$, so (as proved last time) $G \cong (\mathbb{Z}/4\mathbb{Z})$.
- (2) $\nexists g \in G, |g| = 4$:

So $G = \{e_G, a, b, c\}$, meaning $|e_G| = 1$ and $|a| = |b| = |c| = 2$. So $\forall g \in G (g^2 = e_G)$. Hence G is abelian (Homework). What is ab ? It's not e_G as $a^{-1} = a \neq b$. It's not a since $b \neq e_G$. It's not b since $a \neq e_G$. So $ab = c$. Thus we may write the multiplication table.

Verification that $G \cong (\mathbb{Z}/2\mathbb{Z}) \times (\mathbb{Z}/2\mathbb{Z})$ is left to the reader.

□

Remark. More generally, if p prime and $|G| = p^2$ then $G \cong (\mathbb{Z}/p^2\mathbb{Z})$ or $G \cong (\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/p\mathbb{Z})$.

Proposition 8.17. *Suppose G is a group and $|G| = 6$. Then $G \cong (\mathbb{Z}/6\mathbb{Z})$ or $G \cong S_3$.*

Proof. (Sketch)

If $\exists x \in G$ with $|x| = 6$ then $G = \langle x \rangle \cong (\mathbb{Z}/6\mathbb{Z})$.

More subtly, if $\exists a, b \in G$ such that $|a| = 3$ and $|b| = 2$ and $ab = ba$ then $G \cong (\mathbb{Z}/6\mathbb{Z})$ (verification that $|ab| = 6$ left as an exercise to the reader).

WLOG, assume all non-identity elements have order 2 or 3.

Also, elements of order 3 come in pairs. $|x| = 3, |x^{-1}| = 3, x \neq x^{-1}$. So $|\{x : |x| = 3\}| \in \{0, 2, 4\}$ (as it must be even, and $|e_G| = 1 \neq 3$).

Possible order breakdowns: either (A): 1 2 2 2 2 2, (B): 1 2 2 2 3 3, or (C): 1 2 3 3 3 3.

Claim (1). (A) can't happen. Why? Assume otherwise, then $\forall x \in G (x^2 = e)$ so G is abelian, so $\{1, a, b, ab\}$ is a subgroup, but $4 \nmid 6$. so by Lagrange's theorem, this cannot happen.

Claim (2). (C) also cannot happen. Why? Assume otherwise, then denote by x the unique element of order 2. Then, $\forall g \in G, g^{-1}xg$ also has order 2. as

$$g^{-1}xgg^{-1}xg = g^{-1}x^2g = g^{-1}g = e$$

Thus, $g^{-1}xg$ has order 2. $\forall g \in G, g^{-1}xg = x \implies xg = gx$, contradiction.

Claim (3). (B) forces $G \cong S_3$. Proof of this follows from brute force considering the multiplication table.

□(outline)

9. Group Actions

“Groups, like men, shall be judged by their actions.” – Unknown

Definition 9.1. Suppose G is a group (not necessarily finite), and X is a set (also not necessarily finite). A group action of G on X is formally a function $a : G \times X \rightarrow X$ such that $\forall x \in X : a(e_G, x) = x$, and $\forall g, h \in G, x \in X : a(gh, x) = a(g, a(h, x))$.

Notation. We write actions like this: $G \curvearrowright X$ “ G acts on X ,” and $g \cdot x := a(g, x)$. The conditions then become $e_G \cdot x = x$ and $(gh) \cdot x = g \cdot (h \cdot x)$.

Equivalently, instead of thinking about an action as a function of $(G \times X) \rightarrow X$, you can view it as a (“curried”) function of $G \rightarrow (X \rightarrow X)$.

Say $g \mapsto \sigma_g$ where $\sigma_g \cdot (X \rightarrow X)$ is defined by $\sigma_g(x) = g \cdot x = a(g, x)$.

Claim. $\forall g \in G, \sigma_g$ is a permutation of X .

Proof. $\sigma_g \circ \sigma_{g^{-1}} = \sigma_{g^{-1}} \circ \sigma_g = \sigma_{e_G} (= x \mapsto x)$.

Why?

$$\sigma_g \circ \sigma_{g^{-1}}(x) = g \cdot (g^{-1} \cdot x) = (gg^{-1}) \cdot x = e_G \cdot x = x = \sigma_{e_G}(x)$$

Thus, σ_g is a bijection. □

An action then induces a map $G \rightarrow S_X, g \mapsto \sigma_g$. Note that $\sigma_g \circ \sigma_h = \sigma_{gh}$.

Property 9.2. Actions of G on X correspond to homomorphisms $G \rightarrow S_X$.

Example. Of actions:

- (1) $X = \{1, 2, \dots, n\}, S_n \curvearrowright X$ The action is $\sigma \cdot x = \sigma(x)$.
More generally, if $H \leq S_n$, we get an analogous action.
- (2) Let G be the 2×2 invertible matrices over \mathbb{R} under the operation of matrix multiplication.
 $G \curvearrowright \mathbb{R}^2$ (acts on the Euclidean plane) by applying the matrices’ corresponding linear transformation to the vector in \mathbb{R}^2 . (Verification left to the reader.)
- (3) $G = (\mathbb{R}, +)$ X is a circle. $G \curvearrowright X$ r “rotates the circle r radians c.c.w.”

◀ Lecture 12 (2016–02–10)

Note: group actions can be either left actions or right actions. However, we will only talk about left actions in this course, so we will refer to them exclusively as “actions.”

Alternate def $G \rightarrow S_X$.

Important special case: $X = G$, then $G \curvearrowright G$ (G acts on itself).

There are three main actions:

- $G \curvearrowright G$ by left multiplication. $\forall g \in G, x \in X (= G), g \cdot x = gx$.
- $G \curvearrowright G$ by right multiplication. $g, x \in G, g \cdot x = xg^{-1}$.

- $G \curvearrowright G$ by conjugation. $g \cdot x = gxg^{-1}$. Note that gxg^{-1} is simply x conjugated by g^{-1} , so it doesn't matter whether we write $g^{-1}xg$ or gxg^{-1} .

Theorem 9.3 (Cayley). *Suppose G is a group. Then there is a set X and a subgroup $H \leq S_X$ such that $G \cong H$.*

Moreover, we can choose X to have cardinality $|G|$. (i.e., if $|G| = n$, we can find an isomorphic copy of G inside S_n .)

Proof. Take $X = G$ and consider the action $G \curvearrowright G$ by left multiplication ($g \cdot x = gx$). This induces a homomorphism $\varphi : G \rightarrow S_G$, $\varphi(g) = \lambda_g$ where $\lambda_g(x) = gx$.

Claim. $\text{Ker}(\varphi) = \{e_G\}$.

Proof (Claim): Suppose $g \in G$ such that $\varphi(g) = e \in S_G$. so $\lambda_g = e$.

In particular, $e_G = \lambda_g(e_G) = ge_G = g$, so $g = e_G$. □(Claim)

By the first isomorphism theorem, $G/\text{Ker}(\varphi) \cong \text{Im}(\varphi)$. Denote by H the image of φ . $H \leq S_G$.

$G/\text{Ker}(\varphi) = G/\{e_G\} \cong G$, so $G \cong H$. □(Theorem)

Example. A concrete example:

$$G = (\mathbb{Z}/2\mathbb{Z}) \times (\mathbb{Z}/2\mathbb{Z}) = \{1, a, b, c\}$$

$$\lambda_b : \begin{cases} 1 \mapsto 3 \\ 2 \mapsto 4 \\ 3 \mapsto 1 \\ 4 \mapsto 2 \end{cases} \quad \text{Run cycle decomposition on each}$$

$$G \cong \{e, (1\ 2)(3\ 4), (1\ 3)(2\ 4), (1\ 4)(2\ 3)\} \leq S_4.$$

This is sometimes called the left multiplication permutation representation of a group.

Remark. Cayley's theorem is not always "optimal." Sometimes $|G| = n$ and $m < n$ such that $H \leq S_m$ and $G \cong H$.

Example. $(\mathbb{Z}/6\mathbb{Z}) = G$, $|G| = 6$. Take $\sigma = (1\ 2\ 3)(4\ 5) \in S_5$.

Then $H = \langle \sigma \rangle \cong (\mathbb{Z}/6\mathbb{Z}) = G$, but $H \leq S_5$ and $5 < 6$.

10. Orbit Equivalence Relations

Definition 10.1. Suppose $G \curvearrowright X$. Define a relation \sim on X by $x \sim y$ iff $\exists g \in G : g \cdot x = y$. This \sim is called the orbit equivalence relation.

Proposition 10.2. \sim is an equivalence relation.

Proof. 3 properties:

- Reflexivity:

$$x \in X. e_G \cdot x = x, \text{ so } x \sim x$$

- Symmetry:

Suppose $x \sim y$. Fix $g \in G$ such that $g \cdot x = y$. Compute $g^{-1} \cdot y = g^{-1} \cdot (g \cdot x) = (gg^{-1}) \cdot x = e_G \cdot x = x$. So $y \sim x$

- Transitivity:

Suppose $x \sim y, y \sim z$. Fix $g, h \in G$ such that $g \cdot x = y$ and $h \cdot y = z$. So $(hg) \cdot x = h \cdot (g \cdot x) = h \cdot y = z$, so $x \sim z$

It follows that \sim is an equivalence relation. \square

Definition 10.3. The equivalence classes of \sim are called orbits. Write them like \mathcal{O}_x . Because \sim is an equivalence class, $\{\mathcal{O}_x\}_{x \in X}$ partitions X .

Notation. Sometimes we write $G \cdot x$ to denote the orbit of x .

◀ Lecture 13 (2016–02–12)

Definition 10.4. $G \curvearrowright X$, fix $x \in X$. The stabilizer of x is $G_x = \{g \in G : g \cdot x = x\} \subseteq G$.

Proposition 10.5. If G is a group then $G_x \leq G$.

Proof. Homework Question \square

Example. Let's look at some examples of group actions and stabilizers of some the elements of the sets they act on.

- (1) $\sigma \in S_5$, say $\sigma = (1\ 3\ 4)(2\ 5)$. $S_5 \curvearrowright \{1, 2, 3, 4, 5\}$. This induces an action of $\langle \sigma \rangle \curvearrowright \{1, 2, 3, 4, 5\}$. (Note that $|\sigma| = 6$.)

$G = \langle \sigma \rangle = \{e, \sigma, \dots, \sigma^5\}$. $X = \{1, 2, 3, 4, 5\}$. Look at $x = 3$. $\mathcal{O} = \{1, 34\}$ = the cycle containing 3 in the cycle decomposition of σ .

If we check each exhaustively, we find $e \cdot 3 = 3$ and $\sigma^3 \cdot 3 = 3$ so the stabilizer of G_3 is $\{e, \sigma^3\}$.

In general, if you have any perm group, the orbit of an element of the cyclic subgroup generated by an element in the permutation group is going to be the cycles and the stabilizers are going to be the lengths of the cycles.

- (2) $G \curvearrowright G$ by left multiplication. $g \cdot x = gx$

Claim. $\forall x \in G, \mathcal{O}_x = G$ (its orbit is G).

Proof. Fix $x \in G$, Fix $g \in G$. Choose $h = gx^{-1}$, then $h \cdot x = (gx^{-1}) \cdot x = (gx^{-1})x = g(x^{-1}x) = g$. Thus, $g \in \mathcal{O}_x$. Thus, $\mathcal{O}_x = G$. \square

Claim. $\forall x \in G, G_x = \{e_G\}$.

Proof. Fix x . Suppose $g \in G$. $g \cdot x = x$.

Thus, $gxx^{-1} = xx^{-1}$ (as $X = G$), so $g = e_G$. \square

- (3) $S_3 \curvearrowright S_3$ by conjugation. $g \cdot x = gxg^{-1}$.
Orbits $\{e\}, \{(1\ 2), (1\ 3), (2\ 3)\}, \{(1\ 2\ 3), (1\ 3\ 2)\}$
 The stabilizer of $(1\ 2)$ is $\{e, (1\ 2)\}$.

- (4) $H \leq G$. Let $H \curvearrowright G$ by right multiplication. Then

$$\mathcal{O}_{x \in G} = \{h \cdot x : h \in H\} = \{xh^{-1} : h \in H\} = \{xh : h \in H\} = xH.$$

Thus, the orbits of the elements of G are the left cosets of H in G .

Definition 10.6. Suppose $G \curvearrowright X$ with a single orbit $\mathcal{O} = X$.

We say that the action is transitive

Definition 10.7. Orbits of the conjugation action of $G \curvearrowright G$ are called conjugacy classes.

Theorem 10.8 (Orbit-Stabilizer Theorem). *Suppose G is a finite group, X is some set, and $G \curvearrowright X$. Fix arbitrarily $x \in X$ with orbit $\mathcal{O} \subseteq X$ and stabilizer $G_x \leq G$. Then $|\mathcal{O}| \cdot |G_x| = |G|$.*

Proof. Define two equivalence relations on G .

- (1) $g \sim h$ iff $g^{-1}h \in G_x$ (left coset equivalence of stabilizers)
- (2) $g \approx h$ iff $g \cdot x = h \cdot x \in X$

For the reader: check \sim and \approx are equivalence relations.

Claim (1). Each \sim equivalence class has $|G_x|$ many elements in it.

Proof. Already done

\square (Claim 1)

Claim (2). There are exactly $|\mathcal{O}|$ -many \approx equivalence classes.

Proof. For each $y \in \mathcal{O}$, put $A_y = \{g \in G : g \cdot x = y\}$. The collection of $\{A_y : y \in \mathcal{O}\}$ is exactly the set of \approx -equivalent classes.

In other words, \approx is partitioning G by the elements which move x into each particular element of \mathcal{O} . \square (Claim 2)

Claim (3). $\sim \cong \approx$

Proof. First show $g \sim h \implies g \approx h$, then show $g \approx h \implies g \sim h$.

- Suppose $g^{-1}h \in G_x$, then $(g^{-1}h) \cdot x = x$, so $g^{-1} \cdot (h \cdot x) = x$.
 Act by g on both sides. $g \cdot x = g \cdot (g^{-1} \cdot (h \cdot x)) = (gg^{-1}) \cdot (h \cdot x) = h \cdot x$, so $g \approx h$.
- Suppose $g \cdot h = h \cdot x$. Act by g^{-1} on both sides. $g^{-1} \cdot (g \cdot h) = g^{-1}(h \cdot x)$.
 $x = e_G \cdot x = (g^{-1}h) \cdot x$, thus $g^{-1}h \in G_x$.

\square (Claim 3)

So the upshot is that we have a single equivalence relation on G . It has $|\mathcal{O}|$ -many classes. Each class has $|G_x|$ -many elements. Hence $|G| = |\mathcal{O}| \cdot |G_x|$. \square (Theorem 10.8)

Remark. The above theorem also works when G is not finite, however it involves multiplication of ordinals, which is beyond the scope of this course.

◀ Lecture 14 (2016–02–15)

We will continue referencing the Orbit-Stabilizer Theorem for the rest of the week

Example. Fix $p \geq 2$ prime and $c \in \mathbb{Z}^+ = \{1, 2, 3, \dots\}$. How many distinct (up to rotation) necklaces can you make of length p out of c colors of beads?

More formally, let $X = \{\text{sequences of length } p \text{ with entries in } \{1, 2, \dots, c\}\}$. Also, let $G = (\mathbb{Z}/p\mathbb{Z})$ act on X by “rotating the indices” (mod p).

For example, if $x = (1, 2, 1, 2, 3) \in X$, then $\bar{1} \cdot x = (3, 1, 2, 1, 2)$, $\bar{3} \cdot x = (1, 2, 3, 1, 2)$.

Question: How many orbits does this action have?

We know by the Orbit-Stabilizer Theorem that for any $x \in X$, $|\mathcal{O}_x| \cdot |G_x| = |G| = p$. Thus $\{|\mathcal{O}_x|, |G_x|\} = 1, p$. Thus, let us pick an arbitrary necklace $x \in X$ and examine \mathcal{O}_x and G_x .

Case 1: $|\mathcal{O}_x| = 1$. Then $|G_x| = p$. So $g \cdot x = x$ for all $g \in (\mathbb{Z}/p\mathbb{Z})$. This necessitates that every bead in x is the same as the next one, meaning all the beads on x are the same color. As there are c colors, there are exactly c -many possible distinct $x \in X$ in this case.

Case 2: $|\mathcal{O}_x| = p$. Then $|G_x| = 1$. All other $x \in X$ fall into this case. $|X| = c^p$ as there are p places with c choices each. Thus there are $c^p - c$ necklaces falling into this case.

Thus, the total number of orbits is $c + \frac{c^p - c}{p}$. As a nice corollary, this implies that $\frac{c^p - c}{p}$ is an integer, as it is counting something.

Next, we make necklaces out of group elements.

Theorem 10.9 (Cauchy). *Suppose that G is a finite group $|G| = n$ and $p \geq 2$ is a prime such that $p|n$. Then $\exists g \in G$ such that $|g| = p$.*

Proof. Let X be the set of sequences (g_1, g_2, \dots, g_p) of length p with elements from G , such that $\prod_{i=1}^p g_i = e_G$.

Claim (1). $|X| = n^{p-1}$

Proof. Fix g_1, \dots, g_{p-1} . Then $g_p = (g_1 g_2 \dots g_{p-1})^{-1}$ is the unique way to land in X . $\square(\text{C1})$

Claim (2). Suppose $(g_1, g_2, \dots, g_p) \in X$. Then $(g_p, g_1, g_2, \dots, g_{p-1}) \in X$.

Proof. We know $\prod_{i=1}^p g_i = e_G$. Multiplying both sides on the right by g_p^{-1} gives $\prod_{i=1}^{p-1} g_i = g_p^{-1}$. Then, we multiply on the left by g_p to get $g_p \prod_{i=1}^{p-1} g_i = e_G$. Note that this is simply conjugating by g_p . $\square(\text{C2})$

Let $H = (\mathbb{Z}/p\mathbb{Z})$, $H \curvearrowright X$ by “rotation.” So, $\bar{1} \cdot (g_1, g_2, \dots, g_p) = (g_p, g_1, \dots, g_{p-1})$. By claim 2, we note that this is a group action. By the Orbit-Stabilizer Theorem, we have for every $x \in X$, $|\mathcal{O}_x| \cdot |H_x| = |H| = |(\mathbb{Z}/p\mathbb{Z})| = p$. So for every $x \in X$, $|\mathcal{O}_x| = 1$ or p .

Let's say k_1 is the number of orbits of cardinality 1, and k_p is the number of orbits of cardinality p .

Hence, $1 \cdot k_1 + p \cdot k_p = |X| = n^{p-1}$, so $k - 1 = n^{p-1} - p \cdot k_p$. Thus $p|k$.

Claim (3). $k_1 \geq 1$.

Proof. $\underbrace{(e_G, e_G, \dots, e_G)}_{p \text{ times}} \in X \quad \square(\text{C3})$

Thus, by claim 3 and the fact that $p|k$, $k_1 \geq p$. In particular, $k_1 \geq 2$. So there is some $x \in X$ with $x \neq (e_G, e_G, \dots, e_G)$ such that $\mathcal{O}_x = 1$. So $x = (\underbrace{g, g, \dots, g}_{p \text{ times}})$ with $g \neq e_G$.

$x \in X \implies \prod_{i=1}^p g = e_G \implies g^p = e_G$. Thus $|g| = p$, so we're done. \square (Cauchy)

Remark. The above theorem is *false* if p were to be composite.

Lead in to next lecture: Conjugation.

Let $G \curvearrowright G$ by conjugation. $\forall g \in G, \forall x \in G : g \cdot x = gxg^{-1}$

If $x \in G$, what is G_x (under conjugation)?

$$G_x = \{g \in G : g \cdot x = x\} = \{g \in G : gxg^{-1} = x\} = \{g \in G : gx = xg\}$$

In other words, $G_x = \{g \in G : g \text{ commutes with } x\}$.

Definition 10.10. The center of G , denoted $Z(G)$ is the set $\{x \in G : \forall g \in G (gx = xg)\}$.

So $x \in Z(G) \iff G_x = G$ (for conjugation). This is also equivalent to saying $\mathcal{O}_x = \{x\}$.

◀ **Lecture 15 (2016–02–17)**

Class Note

Midterm coming up: February 26th in class (1:30-2:20pm)

Class Plans: Up to spring break, we'll continue talking about groups

After spring break, we'll start ring theory.

Definition 10.11. $G \curvearrowright X$ $x \in X$ is a fixed point of the action if $\forall g \in G (g \cdot x) = x$. (This is equivalent to saying $G_x = G$, or $\mathcal{O}_x = \{x\}$.)

Example.

- (A) $(\mathbb{Z}/n\mathbb{Z})$ acts by “rotation” on “ c^n ” = sequences of length n with elements in $\{1, 2, \dots, c\}$.
Then the fixed points are the constant sequences.
- (B) $G \curvearrowright G$ by left or right multiplication and $G \neq \{e_G\}$, then there are *no* fixed points.
(Take $g \neq e_G$, then $g \cdot h = gh \neq h$.)
- (C) $G \curvearrowright G$ by conjugation. $g \cdot x = gxg^{-1}$. Then x is a fixed point iff $x \in Z(G)$, i.e., $\forall g \in G (xg = gx)$, x commutes with everything in G .

Definition 10.12. Given a prime $p \geq 2$, we say that a finite group G is a p -group if $|G| = p^k$ for some $k \in \mathbb{N}^+$.

Proposition 10.13. *The following are equivalent:*

- (1) G is a p -group
- (2) Every subgroup $H \leq G$ is a p -group
- (3) Every $g \in G$ has $|g| = p^i$ for some $i \in \mathbb{N}$

Proof. Left to the reader. \square

Theorem 10.14 (Fixed-Point Lemma). *Suppose p prime, G is a p -group and $G \curvearrowright X$, and let F be the number of fixed points. Then, $F \equiv |X| \pmod{p}$.*

Proof. Say $|G| = p^k$. By the Orbit-Stabilizer Theorem, for $x \in X$, $|\mathcal{O}_x| \cdot |G_x| = p^k$. so $|\mathcal{O}_x| \in \{1, p, p^2, \dots, p^k\}$.

For $0 \leq i \leq k$, denote by n_{p^i} the number of orbits of size p^i .

$$|X| = \sum_{i=0}^k p^i \cdot n_{p^i}$$

as the orbits partition X . Thus, $|X| - n_1 = \sum_{i=1}^k p^i \cdot n_{p^i}$, so $p \mid (|X| - n_1)$. It follows that $n_1 \equiv |X| \pmod{p}$, as desired. $\square(\text{Lem})$

Corollary 10.14.1. *Suppose p prime and $G \neq \{e\}$ is a p -group. Then $|Z(G)| \geq p$.*

Proof. $|Z(G)|$ = number of fixed points of $G \curvearrowright G$ by conjugation. Thus, by the Fixed-Point Lemma, $|Z(G)| \equiv |G| \pmod{p}$. So, $|Z(G)|$ is a multiple of p .

Claim. $|Z(G)| \neq 0$. This is true as $e_G \in Z(G)$.

Thus, $|Z(G)| \geq p$. $\square(\text{Cor})$

Proposition 10.15. *Suppose p prime, G is a group with $|G| = p^2$. Then, $G \cong (\mathbb{Z}/p^2\mathbb{Z})$ OR $G \cong ((\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/p\mathbb{Z}))$.*

Proof. If $\exists g \in G$ with $|g| = p^2$ then $\langle g \rangle = G$, so $G \cong (\mathbb{Z}/p^2\mathbb{Z})$.

Otherwise, all non-identity elements of G have order p .

Since $|Z(G)| \geq p \geq 2$, we may fix non-identity $h \in Z(G)$. The set $\langle h \rangle$ has cardinality p . Now pick $k \in G \setminus \langle h \rangle$. Put $H := \langle h \rangle$ and $K := \langle k \rangle$, both with cardinality p .

Claim. The map $\varphi : ((\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/p\mathbb{Z})) \rightarrow G$ with $\varphi(\bar{i}, \bar{m}) = h^i k^m$ is an isomorphism. (\bar{i} and \bar{m} are residue classes of $(\mathbb{Z}/p\mathbb{Z})$.) Note that if $i, j \in \bar{i}$, then $h^i = h^j$, so $h^i(h^j)^{-1} = h^{i-j} = h^{pa} = e_G$.

Proof. First we show φ is a homomorphism, i.e., $\varphi(\bar{i} + \bar{j}, \bar{m} + \bar{n}) = (h^i k^m)(h^j k^n) = \varphi(\bar{i}, \bar{m})\varphi(\bar{j}, \bar{n})$. \blacksquare

It is apparent that $\varphi(\bar{i} + \bar{j}, \bar{m} + \bar{n}) = h^{i+j} k^{m+n} = h^i h^j k^m k^n$. However, as h is in the center of G , h and k commute, so $h^i h^j k^m k^n = h^i k^m h^j k^n$ as desired.

Next we show that φ is an isomorphism by showing it is also a bijection.

Since $|((\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/p\mathbb{Z}))| = |G| = |p^2|$, to show φ is bijective, it suffices to show that φ is *injective*. In turn, it is sufficient to prove $\text{Ker}(\varphi) = \{e_G\}$.

As we proved in a homework, $H \cap K \leq H$, so $|H \cap K|$ is 1 or p . $k \notin H \cap K$, so $|H \cap K| \leq |K|$. Thus, as the cardinality of the intersection must divide p^k , the intersection has cardinality 1, meaning $H \cap K = \{e_G\}$.

Suppose $\bar{i}, \bar{m} \in (\mathbb{Z}/p\mathbb{Z})$ with $\varphi(\bar{i}, \bar{m}) = e_G$. Then $h^i k^m = e_G$. Thus, $\underbrace{h^i}_{\in H} = \underbrace{k^{-m}}_{\in K}$. Since $h^i = k^{-m} \in H \cap K$, $h^i = k^{-m} = e_G$. So i, m are multiples of p . Hence, $(\bar{i}, \bar{m}) = (\bar{0}, \bar{0})$. Thus $\text{Ker}(\varphi) = \{e_G\}$, so φ is injective as desired, meaning φ is an isomorphism. $\square(\text{prop})$

\square

◀ Lecture 16 (2016–02–19)

Class Note

Review sheet for Midterm 1 will be posted this afternoon.
(Exam on February 26th in class).

Conjugation in S_n .

Example. Suppose $\sigma = (1\ 3\ 4)(2\ 5) \in S_5$ and $\tau = (1\ 2\ 3\ 4\ 5) \in S_5$. What is $\tau\sigma\tau^{-1}$?
Compute $\tau^{-1} = (1\ 5\ 4\ 3\ 2)$.

So, $\tau\sigma\tau^{-1} = (1\ 2\ 3\ 4\ 5)(1\ 3\ 4)(2\ 5)(1\ 5\ 4\ 3\ 2) = (1\ 3)(2\ 4\ 5)$

Proposition 10.16. Suppose $\sigma, \tau \in S_n$. Fix $a, b \in \{1, 2, \dots, n\}$. Suppose $\sigma' := \tau\sigma\tau^{-1}$. If $\sigma(a) = b$ then $\sigma'(\tau(a)) = \tau(b)$

Proof. $\sigma'(\tau(a)) = (\tau\sigma\tau^{-1}\tau)(a) = (\tau\sigma)(a) = \tau(b)$. \square

But why is this useful? Conjugation in S_n is “relabeling.” Revisiting the previous example: $\sigma = (1\ 3\ 4)(2\ 5)$ $\tau\sigma\tau^{-1} = (\tau(1)\ \tau(3)\ \tau(4))(\tau(2)\ \tau(5)) = (2\ 4\ 5)(3\ 1) = (1\ 3)(2\ 4\ 5)$.

We’ve shown: Whenever σ, σ' are conjugate in S_n , then σ, σ' have the same cycle type (i.e. the same number of cycles of each length).

Definition 10.17. The cycle type of a permutation is the number of cycles of each length in the permutation’s cycle decomposition

Theorem 10.18. $\sigma, \sigma' \in S_n$ are conjugate (in S_n) if and only if they have the same cycle type.

Sketch. We know that conjugate \implies same cycle type. For the converse, suppose σ, σ' have the same cycle type.

Shuffle the cycles (because they’re disjoint) in σ to line up with those of σ' .

Then take the permutation that takes the elements in the cycles of σ to the corresponding elements in the cycles of σ' . (Also, make sure that fixed points are sent to fixed points.)

This generates a permutation τ such that $\tau\sigma\tau^{-1} = \sigma'$, so σ and σ' are conjugate. \square (sketch)

Example. $\sigma = (1\ 3)(2\ 5\ 6)(4\ 7) \in S_7$ $\sigma' = (1\ 5\ 7)(2\ 3)(4\ 6) \in S_7$.

Thus, by our last theorem, they are conjugate.

Shuffle σ' to correspond with σ :

$\sigma = (1\ 3)(2\ 5\ 6)(4\ 7)$

$\sigma' = (2\ 3)(1\ 5\ 7)(4\ 6)$

Thus, $\tau = (1\ 2)(3\ 5)(4\ 6)(7)$.

Note that we could have shuffled the cycles differently and come up with a different τ .

Example. Compute the size of every conjugacy class in S_4 . (Where the conjugacy classes are the orbits of $S_4 \curvearrowright S_4$ by conjugation).

By our previous theorem we only have to check each cycle type.

| Cycle Types: | How many with that type? |
|------------------------------|--|
| $(\cdot \cdot \cdot \cdot)$ | $3! = 6$ |
| $(\cdot \cdot \cdot)$ | $\binom{4}{3} \cdot 2! = 8$ |
| $(\cdot \cdot)(\cdot \cdot)$ | $\binom{4}{2} \cdot \binom{2}{2} \cdot \frac{1}{2!} \cdot 1! \cdot 1! = 3$ |
| $(\cdot \cdot)$ | $\binom{4}{2} \cdot 1! = 6$ |
| e | 1 |
| Total: | 24 |

Example. How many elements of S_5 commute with $\sigma = (1\ 4)(3\ 5)$? Use the Orbit-Stabilizer Theorem!

$S_5 \curvearrowright S_5$ by conjugation. \mathcal{O}_σ = the conjugacy class of σ .

$G_\sigma = \{g \in S_5 : g\sigma g^{-1} = \sigma\} = \{g \in S_5 : g\sigma = \sigma g\}$. The Orbit-Stabilizer Theorem says that $|\mathcal{O}_\sigma| \cdot |G_\sigma| = |S_5|$ Thus, as $|\mathcal{O}_\sigma| = 15$ and $|S_5| = 120$ so $|G_\sigma| = \frac{120}{15} = 8$.

Example. How many elements of S_9 commute with $\sigma = (1\ 2)(3\ 4)(5\ 6)(7\ 8\ 9)$?

The size of σ 's conjugacy class is $n = \binom{9}{2} \binom{7}{2} \binom{5}{2} \frac{1}{3!} 1!1!1!2!$

Thus, the number of elements of S_9 commuting with σ is $\frac{9!}{n} =$

◀ Lecture 17 (2016–02–22)

Definition 10.19. If $A, B \subseteq G$, where G is a group (A and B not necessarily). Then put $AB := \{ab : a \in A, b \in B\}$. We note that unless the group is abelian, order still matters.

Caveat: If $H, K \leq G$ are subgroups, then HK is typically *not* a subgroup.

Proposition 10.20. If G is a finite group and $H, K \leq G$ are subgroups, then $|HK| = \frac{|H| \cdot |K|}{|H \cap K|}$.

Proof. Note that $HK = \{hk : h \in H, k \in K\} = \bigcup_{h \in H} hK$. So $|HK| = n \cdot |K|$, where n is the number of left cosets of K meeting H .

Claim. For $h_1, h_2 \in H$: $h_1K = h_2K \iff h_1^{-1}h_2 \in H \cap K$

Proof. (\implies): If $h_1K = h_2K$, then by definition of coset equality, we know that $h_1^{-1}h_2 \in K$. As H is a subgroup of G , $h_1^{-1}h_2 \in H$ also.

(\impliedby): If $h_1^{-1}h_2 \in H \cap K$, it's in K , so $h_1K = h_2K$. □(Claim)

Note that $H \cap K \leq H$. So the number of cosets of $H \cap K$ in H is $\frac{|H|}{|H \cap K|}$. Thus, $n = \frac{|H|}{|H \cap K|}$, meaning that $|HK| = \frac{|H| \cdot |K|}{|H \cap K|}$, as desired. □

Remark. The proposition is especially useful when $H \cap K = \{e_G\}$. In this case, you get $|HK| = |H| \cdot |K|$. This happens, for example, when

- $|H|, |K|$ are relatively prime
- $|H| = |K| = p$ prime, and $H \neq K$.

Corollary 10.20.1. Suppose G is a finite group, and $H, K \leq G$ such that

- (1) $|G| = |H| \cdot |K|$
- (2) $H \cap K = \{1\}$.
- (3) $\forall h \in H, \forall k \in K : hk = kh$.

Then $G \cong H \times K$.

Proof. Consider the map $\varphi : H \times K \rightarrow G$ with $\varphi((h, k)) = hk$.

Claim (1). φ is a homomorphism.

1. Suppose $(h_1, k_1), (h_2, k_2) \in H \times K$. First compute $\varphi((h_1, k_1)(h_2, k_2)) = \varphi((h_1h_2, k_1k_2)) = h_1h_2k_1k_2$. Then compute

$$\begin{aligned} & \varphi((h_1, k_1))\varphi((h_2, k_2)) \\ &= (h_1k_1, h_2k_2) \\ &= h_1(k_1h_2)k_2 \end{aligned}$$

As $hk = kh$ by assumption

$$\begin{aligned} &= h_1h_2k_1k_2 \\ &= \varphi((h_1, k_1)(h_2, k_2)) \end{aligned}$$

So φ is a homomorphism. □(C1)

Claim (2). φ is a bijection.

2. Note $|G| = |H| \cdot |K| = |H \times K|$, which are both finite. So, it suffices to show that φ is a surjection.

$\varphi[H \times K] = \{hk : h \in H, k \in K\} = HK$, and $|HK| = \frac{|H| \cdot |K|}{|H \cap K|}$. Thus $\text{Im}(\varphi) = G$, so φ is surjective. $\square(\text{C2})$

It follows that φ is an isomorphism, so $G \cong H \times K$ as desired. $\square(\text{Cor})$

Theorem 10.21. *Suppose G is finite and $H, K \trianglelefteq G$, such that:*

- $|G| = |H| \cdot |K|$
- $H \cap K = \{e_G\}$

Then $G \cong H \times K$.

Proof. By corollary 10.20.1, it suffices to show that $\forall h \in H, \forall k \in K : hk = kh$. Consider $hkh^{-1}k^{-1}$ (called the commutator).

Claim (1). $hkh^{-1}k^{-1} \in H$

Which is proved by inserting parentheses as follows:

$$\underbrace{h}_{\in H} \underbrace{(kh^{-1}k^{-1})}_{\in H} \in H,$$

where the second containment holds because H is normal.

Claim (2). $hkh^{-1}k^{-1} \in K$. This is true because $(hkh^{-1})k^{-1} \in K$, as K is normal.

Thus, $hkh^{-1}k^{-1} \in H \cap K = \{e_G\}$. So, $hkh^{-1}k^{-1} = e_g \implies hk = kh$. $\square(\text{Thm})$

Next, we act on the set of subgroups by conjugation.

Proposition 10.22. *Let G be a group $H \leq G$ a subgroup, $g \in G$. Then $gHg^{-1} = \{ghg^{-1} : h \in H\}$ is a subgroup of G . Moreover, $gHg^{-1} \cong H$.*

Proof. Put $H' = gHg^{-1}$.

H' is nonempty as $ge_Gg^{-1} = e_G \in H'$.

H' is closed under products because if $gh_1g^{-1}, gh_2g^{-1} \in H'$, then $(gh_1hg^{-1})(gh_2g^{-1}) = g(h_1h_2)g^{-1} \in H'$.

H' is closed under inverses as if $ghg^{-1} \in H$, then $(ghg^{-1})^{-1} = (g^{-1})^{-1}h^{-1}g^{-1} = ghg^{-1} \in H'$

Claim. $\varphi : H \rightarrow H', \varphi(h) = ghg^{-1}$ is an isomorphism.

The proof is left as an exercise to the reader. \square

Hence, G acts on $\{H : H \leq G\}$ by conjugation $g \cdot H = gHg^{-1}$.

In addition, H is a fixed point of this action exactly when $H \trianglelefteq G$.

◀ Lecture 18 (2016–02–24)

Theorem 10.23. *Suppose $p < q$ primes and $q \not\equiv 1 \pmod{p}$. Then every group G with $|G| = pq$ is cyclic. (i.e., $G \cong (\mathbb{Z}/pq\mathbb{Z})$)*

Proof. Let $p = 3, q = 5$, The general case proof is left as an exercise.

Note: $(\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/q\mathbb{Z})$ is cyclic because $|(h, k)| = \text{lcm}(p, q) = pq$ (as they're relatively prime).

So now there is enough to show that $G \cong (\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/q\mathbb{Z})$. By Cauchy, we may take subgroups $H, K \leq G$ with $|H| = p$ and $|K| = q$. We want: $\forall h \in H, \forall k \in K : hk = kh$ (then $G \cong (\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/q\mathbb{Z})$).

First we let K act on the subgroups of G by conjugation. $k \cdot J = kJk^{-1}$
 $|K| = 5$, so every orbit has size 1 or 5 by the Orbit-Stabilizer Theorem. In particular, the orbit of H \mathcal{O}_H has size 1 or 5.

Case 1 $|\mathcal{O}_H| = 1$. I.e., $\forall k \in K : kHk^{-1} = \{khk^{-1} : h \in H\} = H$.

Now let $K \curvearrowright H$ by conjugation. $k \cdot h = khk^{-1}$. Orbits have size 1 or 5. But $|H| = 3$ So every orbit has size 1. I.e., $\forall k \in K, \forall h \in H : khk^{-1} = h$, so $kh = hk$. Hence (in this case), $G \cong H \times K$.

Case 2 $|\mathcal{O}_H| = 5$ I.e., there are 5 distinct subgroups of the form $kHk^{-1}, k \in K$. Then $G = \bigcup_{S \in \mathcal{O}_H} S \cup K$, as each pair of subgroups in \mathcal{O}_H has intersection e_G . Also K exists, so the subgroups of G are either in \mathcal{O}_H or equal to K . Thus, K is the *unique* subgroup of G of cardinality 5. In particular, $\forall g \in G : gKg^{-1}$ also has cardinality 5, so $gKg^{-1} = K$, hence $K \trianglelefteq G$. Let $H \curvearrowright K$ by conjugation. $h \cdot k = hkh^{-1} \in K$.

Claim (1). $\exists k_0 \in K$ such that $k_0 \neq e_G$ and $\forall h \in H : hk_0h^{-1} = k_0$

Proof. Let p be the number of fixed points. By Fixed-Point Lemma, $p \equiv |K| \pmod{3}$. However, $|K| \not\equiv 1 \pmod{3}$, so $p \geq 2$. Thus, there exists a non-identity fixed point $(k_0)^1$. $\square(\text{Claim})$

So, $\forall h \in H : hk_0 = k_0h$. Since $k_0 \neq e$, $|k_0| = 5$, hence $K = \langle k_0 \rangle$. Since $hk_0^n = k_0^n h$, and h was arbitrary, we know that $\forall h \in K, \forall k \in K : hk = kh$. Thus, $G \cong H \times K$. $\square(\text{Thm})$.

Proposition 10.24. ($p=2$) Suppose $q > 2$ is prime. Then there exists (up to isomorphism) a unique non-cyclic group G with $|G| = 2q$.

Proof Sketch. Fix (by Cauchy) $x, y \in G$ such that $|x| = 2, |y| = q$, then put $H = \langle x \rangle$ and $K = \langle y \rangle$.

We posit that $K \trianglelefteq G$ (verification left as an exercise).

So $H \curvearrowright K$ by conjugation. So, $xyx^{-1} \in K \exists r : 0 < r < q$ such that $xyx^{-1} = y^r$, $xy^2x^{-1} = (xyx^{-1})(xyx^{-1}) = y^{2r}$. Thus, it is apparent that $xy^jx^{-1} = y^{jr \pmod{q}}$

But also,

$$y = x^2y^2x^{-2} = x(xy x^{-1})x^{-1} = x(y^r)x^{-1} = y^{r \cdot r}$$

So, $r^2 \equiv 1 \pmod{q}$

Exercise: The only solutions to $r^2 \equiv q \pmod{q}$ are $r \equiv 1, -1 \pmod{q}$.

Case 1 ($r = 1$): $xyx^{-1} = y$, i.e., $xy = yx$. Hence, $G \cong \langle x \rangle \times \langle y \rangle = H \times K$, cyclic.

Case 2 ($r = -1$): $xyx^{-1} = y^{-1}$. Shuffle to obtain $yx = xy^{-1}$.

We know that $G = \{x^i y^j : i \in \{0, 1\}, j \in \{0, \dots, q-1\}\} = HK$.

To multiply, $(x^i y^j)(x^\ell y^k) = \begin{cases} (x^i y^{j+k}) & \text{if } \ell = 0 \\ x^i (y^j x) y^k = x^i x y^{-j} y^k = x^{i+1} y^{k-j} & \text{if } \ell = 1 \end{cases}$

Hence, the group operation is completely determined by $yx = xy^{-1}$, and so there is at most one non-cyclic group (up to isomorphism) of cardinality $(\mathbb{Z}/q\mathbb{Z})$.

To show the existence of such a group, given $n \geq 3$, we consider the dihedral group of cardinality $2n$, where the dihedral group is the group generated by reflection and rotation on the regular n -polygon. \square

¹Note that this is where we needed the hypothesis that $q \not\equiv 1 \pmod{p}$.

◀ Lecture 19 (2016–02–29)

Definition 10.25. Let $H \leq G$ be groups. The normalizer of H in G is $N_G(H) = N(H) = \{g \in G : g^{-1}Hg = H\} = \{g \in G : gHg^{-1} = H\}$

Fact/Exercise:

- (1) $N(H) \leq G$
- (2) $H \trianglelefteq N(H)$

Theorem 10.26 (Sylow 1). Suppose that G is a finite group, p is prime, and p^i divides $|G|$ for some $i \in \mathbb{Z}$. Then $\exists H \leq G$ such that $|H| = p^i$.

Proof. Proceed by induction on i .

If $i = 0$ then trivial as $H = \{e\}$, the trivial subgroup. If $i = 1$ then this is true by Cauchy.

Our strategy is to suppose we have $H_i \leq G$ of cardinality $|H_i| = p^i$. and p^{i+1} divides $|G|$. We will find $H_{i+1} \supseteq H_i$ with $H_{i+1} \leq G$ and $|H_{i+1}| = p^{i+1}$.

Intuition: Consider the cosets of H_i in G . We're going to pick out p cosets of H_i $g_1H_i, g_2H_i, \dots, g_pH_i$ such that $\bigcup_{i=1}^p g_iH_i$ is a subgroup of G .

Let $X = G/H_i = \{gH_i : g \in G\}$. Note that $|X| = \frac{|G|}{|H_i|} = \frac{p^z m}{p^i}$ (where $z > i$) $\equiv 0 \pmod{p}$.

Let $H_i \curvearrowright X$ by left multiplication. $h \cdot (gH_i) = (hg)H_i$.

Claim (1). $gH_i \in X$ is a fixed point of the action iff $g \in N(H_i)$.

Proof. gH_i is a fixed point iff $\forall h \in H_i (h \cdot (gH_i) = gH_i)$ iff $(hg)H_i = gH_i$ iff $g^{-1}hg \in H_i$.

Thus, $g^{-1}H_i g \in H_i$ so, as they are finite sets with the same cardinality and conjugation is an injective map, $g^{-1}H_i g = H_i$, meaning $g \in N(H_i)$ □(C1)

By Fixed-Point Lemma, since H_i is a p -group, we know that $\#$ fixed points $\equiv |X| \pmod{p}$. The number of cosets fixed by the action is a multiple of p . This is equivalent to saying p divides $|N(H_i)/H_i|$ (i.e., the number of cosets represented in the normalizer is a multiple of p). Since $H_i \trianglelefteq N(H_i)$, $N(H_i)/H_i$ is a quotient group. So by Cauchy, we may take $g \in N(H_i)$ such that $|gH_i| = p$ in $N(H_i)/H_i$.

Intuition: As we cycle through the powers of g , we get the cosets we're going to choose.

Finally, let $H_{i+1} = \bigcup_{k=0}^{p-1} g^k H_i = \{g^k h : h \in H_i, 0 \leq k < p\}$.

Note that $|H_{i+1}| = p^{i+1}$ as it's a union of p disjoint cosets of cardinality p^i .

Claim (2). H_{i+1} is a subgroup of G .

Proof.

- $e_G \in H_{i+1}$
- $h_1, h_2 \in H_{i+1} \implies h_1 h_2 \in H_{i+1}$
 Fix k, ℓ such that $x, y \in H_i$ and $h_1 = g^k x, h_2 = g^\ell y$.
 Since $g \in N(H_i)$, $\exists z \in H_i$ such that $g^{-\ell} x g^\ell = z$. So,

$$h_1 h_2 = g^k x g^\ell y = g^{k+\ell} \underbrace{zy}_{\in H_i} \in H_{i+1}$$

□(C2)

□(Thm)

Definition 10.27. For p prime, $H \leq G$ (finite), is a Sylow p -subgroup if $|H|$ is the largest power of p dividing $|G|$. i.e., if, $|G| = p^k m$, $\gcd(p, m) = 1$. Then $|H| = p^k$.

Theorem 10.28 (Sylow 2). *Any two Sylow p -subgroups of G (finite) are conjugate.*

Proof will come later.

Theorem 10.29 (Sylow 3). *If $|G| = p^k m$, $\gcd(p, m) = 1$, then the number of Sylow p -subgroups n_p satisfies $n_p | m$ and $n_p \equiv 1 \pmod{p}$.*

Proof will come next lecture, first let's see an example.

Example.

- a) Every group G with $|G| = 15 = 3 \cdot 5$ is cyclic.
 $n_3 | 5 \implies n_3 \in \{1, 5\}$ and $n_3 \equiv 1 \pmod{3}$, so $n_3 = 1$. $n_5 = 1$. Thus, $\exists H, K \trianglelefteq G$ with $|H| = 3, |K| = 5$. So, by Corollary 10.20.1, $G \cong H \times K$.
- b) There are (up to isomorphism) exactly two groups G with cardinality $99 = 3^2 \cdot 11$. Sylow 3-subgroup has cardinality 9. $n_3 = \#$ of subgroups of cardinality 9.
 $n_3 | 11 \implies n_3 \in \{1, 11\}$. As $n_3 \equiv 1 \pmod{3}$, it can't be 11, so $n_3 = 1$
 $n_{11} = \#$ of subgroups of cardinality 11. $n_{11} | 9$ and $n_{11} \equiv 1 \pmod{11}$ means that $n_{11} = 1$.
 Fix unique $H, K \trianglelefteq G$ with $|H| = 9, |K| = 11, H \cap K = \{e\}$. So $G \cong H \times K$.
 Case 1: $H \cong \mathbb{Z}/9\mathbb{Z}$. Then $G \cong \mathbb{Z}_9 \times \mathbb{Z}_{11} \cong \mathbb{Z}_{99}$.
 Case 2: $H \cong \mathbb{Z}_3 \times \mathbb{Z}_3$ then $G \cong \mathbb{Z}_3 \times \mathbb{Z}_3 \times \mathbb{Z}_{11} \cong \mathbb{Z}_3 \times \mathbb{Z}_{33}$.

◀ Lecture 20 (2016–03–02)

Proof of Sylow 2. Fix two Sylow p -subgroups $P, Q \leq G$ such that $|P| = |Q| = p^k$. Let $X = G/P$ and let $Q \curvearrowright X$ by left multiplication, i.e., $\forall h \in Q : h \cdot (gP) = (hg)P$.

Note that $|X| = \frac{p^k m}{p^k} = m \not\equiv 0 \pmod{p}$. Since Q is a p -group, by Fixed-Point Lemma, the number of fixed points is equivalent to $|X| \pmod{p}$, so we can choose a fixed point $gP \in X$. We know that for any $h \in Q, h \cdot (gP) = gP$, so $(hg)P = gP$, meaning $g^{-1}hg \in P$. As $h \in Q$ was arbitrary, $g^{-1}Qg \subseteq P$. As $|g^{-1}Qg| = |P| = p^k$, it follows that $g^{-1}Qg = P$. \square

We prove both parts of Sylow 3 separately, as they are somewhat dissimilar

Proof of Sylow 3 (a). Let $X = \{H \leq G : |H| = p^k\}$ be the set of all Sylow p -subgroups of G . so $|X| = n_p$. Let $G \curvearrowright X$ by conjugation, i.e., $g \cdot H = gHg^{-1}$. For convenience, fix some designated Sylow p -subgroup $P \in X$ (which exists by Sylow 1).

This time we're going to use the Orbit-Stabilizer Theorem

By Sylow 2, we know that $\mathcal{O}_P = X$, so $|\mathcal{O}_P| = n_p$. By the Orbit-Stabilizer Theorem, we know that $|\mathcal{O}_P| \cdot |G_P| = |G|$, so $n_p = |G|/|G_P|$. Note also that $|G| = p^k m$.

Note that $P \leq G_P$ since $\forall g \in P, gPg^{-1} = P$. So, by Lagrange's Theorem, we know that $|P|$ divides $|G_P|$, so say $|G_P| = p^k \ell$. Thus, $n_p = \frac{p^k m}{p^k \ell} = \frac{m}{\ell}$. This shows that $m = n_p \ell$, meaning that n_p divides m as desired. \square

Proof of Sylow 3 (b). Again let $X = \{H \leq G : |H| = p^k\}$ be the set of all Sylow p -subgroups of G . so $|X| = n_p$. Fix $P \in X$ (which exists by Sylow 1). Let $P \curvearrowright X$ by conjugation.

We know that $P \in X$ is a fixed point of $P \curvearrowright X$.

Claim. P is the only fixed point.

Proof (Claim). Suppose $Q \in X$ is a fixed point. Want to show $Q = P$. So, $\forall g \in P, g^{-1}Qg = Q$, i.e., $P \leq N(Q)$. We also know that $Q \leq N(Q)$. So, P, Q are both Sylow p -subgroups of $N(Q)$. By Sylow 2, $\exists h \in N(Q)$ st $Q = h^{-1}Qh = P$. Hence, $Q = P$. \square (Claim)

So the number of fixed points of $P \curvearrowright X$ is 1. P is a p -group, so by the Fixed-Point Lemma, we have $n_p = |X| \equiv 1 \pmod{p}$ \square (Sylow 3b)

Example. Let's classify all *abelian* groups G with cardinality 108 (up to isomorphism). First we note that $108 = 2^2 \cdot 3^3$

By Sylow 1, there exist $H, K \leq G$ such that $|H| = 2^2$ and $|K| = 3^3$.

Since G is abelian, $H \trianglelefteq G$ and $K \trianglelefteq G$.

Also, $H \cap K = \{e\}$ by Lagrange's Theorem (since $\gcd(2^2, 3^3) = 1$). So by corollary 10.20.1, $G \cong H \times K$.

(We write \mathbb{Z}_n for $\mathbb{Z}/n\mathbb{Z}$, although some number theorists would beg to differ.)

First H . H is isomorphic to either \mathbb{Z}_4 or $\mathbb{Z}_2 \times \mathbb{Z}_2$.

Next, K . $|K| = 27$ and it's abelian (because it's a subgroup of G .)

Case 1 ($\exists k \in K$ such that $|k| = 27$):

In this case, $K \cong \mathbb{Z}_{27}$

Case 2 (No element of order 27, but $\exists k \in K$ such that $|k| = 9$):

We posit that we may take $g \in K/\langle k \rangle$ with $|g| = 3$. (Existence left as an exercise to the reader).

$\langle g \rangle \cap \langle k \rangle = \{e\}$. Thus, by corollary 10.20.1, $K \cong \mathbb{Z}_9 \times \mathbb{Z}_3$

Case 3 (All elements have order 3):

Exercise: use Sylow's theorem to show $K \cong (\mathbb{Z}_3 \times \mathbb{Z}_3) \times \mathbb{Z}_3$

These cases are exhaustive, so we have 6 options.

Thus, G could be isomorphic to the direct product of any tuple in $\{\mathbb{Z}_4, \mathbb{Z}_2 \times \mathbb{Z}_2\} \times \{\mathbb{Z}_{27}, \mathbb{Z}_9 \times \mathbb{Z}_3, \mathbb{Z}_3 \times \mathbb{Z}_3 \times \mathbb{Z}_3\}$

Cool note: we won't get to this, but every finite abelian group is isomorphic to the direct product of a direct product of cyclic groups.

11. Ring Theory

◀ Lecture 21 (2016–03–14)

Definition 11.1. A ring is a set R equipped with the binary operations $+$ and \times such that the following axioms are true:

- (1) $(R, +)$ is an abelian group
- (2) \times is associative over R
- (3) \times distributes over $+$ i.e., $a \times (b + c) = (a \times b) + (a \times c)$, also, $(a + b) \times c = (a \times c) + (b \times c)$

Notation. We follow the following conventions:

- We usually don't write \times . Instead we write expressions like $(a \times b) + c$ as $ab + c$.
- The ring R has the additive identity 0.
- we denote the additive inverse of an element $b \in R$ by $-b$

Definition 11.2. A ring R is commutative if \times is commutative ($\forall a, b \in R (a \times b = b \times a)$)

Definition 11.3. The ring R has an identity (or a 1) if $\exists 1 \in R (\forall a \in R (1a = a1 = a))$

Remark. If R has a 1, then it is unique. Why? If $1, e$ are both \times identities, then $1 = 1e = e$.

Definition 11.4. If R has a 1 with $1 \neq 0$ we say R is a division ring if $(R \setminus \{0\}, \times)$ is also a group. (i.e., for all $a \in R, a \neq 0 (\exists b \in R), b \neq 0$ st $ab = ba = 1$ ($b = \frac{1}{a}$))

Definition 11.5. R is a field if it is a commutative division ring.

Example. \mathbb{Q} is a field

Proposition 11.6. Let R be a ring. Then $\forall a \in R, 0a = a0 = 0$.

Proof.

$$0 = 0 + 0$$

Multiply by a

$$0a = (0 + 0)a = 0a + 0a$$

Add $-0a$ to both sides

$$0 = 0a$$

□

Remark. If R has a 1 with $1 = 0$ then $R = \{0\}$. Why? $\forall a \in R, a = 1a = 0a = 0$.

Proposition 11.7.

- (1) $(-a)b = a(-b) = -(ab)$
- (2) $(-a)(-b) = ab$
- (3) If $1 \in R$ then $-a = (-1)a$

Proof. To show $(-a)b = -(ab)$ we check $(-a)b + ab = 0$.
 $(-a)b + ab = (-a + a)b = 0b = 0$. Thus, $(-a)b = -(ab)$.
 The rest are left as an exercise. \square

Definition 11.8. R is a ring, $a \in R$ is a zero-divisor if:

- (1) $a \neq 0$
- (2) $\exists b \neq 0$ such that $ab = 0$ or $ba = 0$

Definition 11.9. R ring with a $1 \neq 0$, $u \in R$ is a unit if $\exists v \in R$ such that $uv = vu = 1$.

Remark. Denote by R^\times the set of units. Then (R^\times, \times) forms a group.

Remark. Since $0 \neq 1$ 0 is never a unit since $0v = 0 \neq 1$.

Proposition 11.10. *No zero-divisor is a unit*

Proof. Towards a contradiction, suppose $a \neq 0$ is both a zero-divisor and a unit. Fix $b \neq 0$ and $v \in R$ such that $ab = 0$ and $va = 1$ (if $ba = 0$ use $av = 1$) $b = 1b = (va)b = vab = v(ab) = v0 = 0$ So $b = 0$ contradiction \square

Example.

- (1) $(\mathbb{Z}, +, \times)$ with the usual $+$ and \times is a commutative ring with a $1 \neq 0$. \mathbb{Z} has no 0-divisors. The units are $\mathbb{Z}^\times = \{1, -1\}$.
- (2) \mathbb{Q} are a commutative ring with a $1 \neq 0$. \mathbb{Q} has no 0-divisors. The units are $\mathbb{Q}^\times = \mathbb{Q} \setminus \{0\}$. So \mathbb{Q} is a field.
- (3) $R = \mathbb{Z}/n\mathbb{Z}$ with modular arithmetic and $\bar{a} \times \bar{b} = \overline{ab}$. If $n > 1$ then R is a ring. R has a 1, namely $\bar{1}$. $\bar{1} \neq \bar{0}$. Commutative.

Claim (C1). Suppose $\bar{a} \neq \bar{0}$ with $\gcd(a, n) = d \neq 1$. Then, \bar{a} is a zero-divisor.

Pf of C1. Choose $b = \frac{n}{d}$ such that $0 < b < n$. So $\bar{b} \neq \bar{0}$. But $\bar{a}\bar{b} = \overline{\left(\frac{a}{d} \times d\right) \times \frac{n}{d}} = \overline{\frac{a}{d} \times n} = \bar{0}$. $\square(C1)$

Claim (C2). Suppose $\bar{a} \neq \bar{0}$ with $\gcd(a, n) = 1$. Then a is a unit.

Pf of C2. Fix $x, y \in \mathbb{Z}$ such that $ax + ny = 1$. $\bar{x}\bar{a} = \overline{ax} = \overline{ax} = \bar{1} \pmod{n}$ $\square(C2)$

Corollary 11.10.1. *If p prime then $\mathbb{Z}/p\mathbb{Z}$ is a field because everything is relatively prime to p .*

◀ Lecture 22 (2016–03–16)

Digression

This is simply a digression. You are *not* responsible for this material.

Can we “test” whether two groups are isomorphic? What is “group data?” Typically, in practice, it’s some sort of combinatorial presentation. We realize groups as words in some (typically finite) alphabet with “substitution rules.” (Relations to automata theory.) Letters are usually called generators, substitution rules called relations, the entire thing is called a presentation.

Typical data: List of letters and substitution rules $\underbrace{\langle x, y, z, \dots \rangle}_{\text{letters}} \mid \underbrace{x^2 = \epsilon, yzy = z^2, \text{etc.}}_{\text{rules}}$.

The group action is typically concatenation (also allowing “inverses” of letters).

Example.

- $G = \langle x \mid \cdot \rangle \cong \mathbb{Z}$
- $G = \langle x \mid x^n = \epsilon \rangle \cong \mathbb{Z}/n\mathbb{Z}$
- $G = \langle x, y \mid xy = yx \rangle \cong \mathbb{Z} \times \mathbb{Z}$ ($(a, b) \mapsto x^a, y^b$ is an isomorphism)
- $G = \langle x, y \mid x^2 = \epsilon, y^m = \epsilon, yx = xy^{-1} \rangle \cong D_{2m}$. $(x^i y^j)(x^k y^\ell) = x^i y^j$
- $G = \langle x, y \mid x^2 = \epsilon, y^5 = \epsilon, xyx = y^2, xy^4 xy^3 x = y^3 \rangle$ Let’s look at y . $y = x^2 y x^2 = x(xy x)x = x(y^2)x = xy y x = xy x^2 y x = (xy x)(xy x) = y^4 = y^2 y y = y^2 y^4 y^4 = y^{10} = (y^5)^2 = \epsilon$ We also know that $\epsilon = y^3 = x \epsilon x \epsilon x = x^3 = x x^2 = x$. Thus, $G \cong \{e\}$.

Theorem (Novikov, Adyan-Rabin). *There is no computer program which upon input some presentation of a group correctly answers $G \stackrel{?}{\cong} \{e\}$.*

Proof. Reduce to halting problem. □

The best know algorithm for testing isomorphism given the multiplication table is $\mathcal{O}(n^{\frac{1}{2} \log n})$
Now, back to ring theory.

Example.

4 $\mathbb{Q}[\sqrt{-5}]$ = elements that look like $a + b\sqrt{-5}$, $a \in \mathbb{Q}, b \in \mathbb{Q}$.

$$(a + b\sqrt{-5}) + (c + d\sqrt{-5}) = (a + c) + (b + d)\sqrt{-5}$$

$$(a + b\sqrt{-5}) \times (c + d\sqrt{-5}) = (ac - 5bd) + (ad + bc)\sqrt{-5}$$

It’s a ring because $0 = 0 + 0\sqrt{-5}$

$$1 = 1 + 0\sqrt{-5}.$$

$$1 \neq 0$$

It’s also commutative (check left to reader).

Every non-zero element is a unit (u is a unit iff $\exists v(uv = vu = 1)$)

$$(a + b\sqrt{-5}) \left(\frac{a - b\sqrt{-5}}{a^2 + 5b^2} \right)$$

5 $\mathbb{Q}[x]$ = polynomials of x with rational coefficients. Typical elements are $p(x) = 5, q(x) = x - 7, r(x) = x^{17} - \frac{2}{3} + \frac{1}{7}$. $+, \times$ as usual. Checking the other ring properties left as an exercise.

Polynomials have no zero divisors. $p(x)q(x) = 0 \iff p(x) = 0$ or $q(x) = 0$.
Takes a little bit of work to show.

x is *not* a unit. No solution to $xp(x) = 1$ (can formalize by looking at the degree of each side).

6 2×2 matrices over \mathbb{Q} . $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$, $a, b, c, d \in \mathbb{Q}$ with normal $+, \times$. *Not* commutative ($AB \neq BA$) in general. $0 = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$, $1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$.

Claim (1). If $\det A \neq 0$ then A is a unit.

Proof. $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$, $A^{-1} = \frac{1}{\det A} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$. □

Claim (2). If $\det A = 0$ then A is a zero-divisor.

Proof. $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix} = 0$ □

Definition 11.11. If R is a ring which

- (1) is commutative
- (2) has a $1 \neq 0$
- (3) has no zero-divisors

then we say R is an integral domain (abbr. ID). (note: integral means like the integers, not like in calculus.)

Proposition 11.12. Suppose R is an ID, $a, b, c \in R$ such that $a \neq 0$ and $ab = ac$. Then $b = c$.

Proof. $0 = ab - ac = a(b - c)$. Since a is not a zero-divisor (because R is an ID) we know that $b - c = 0$. Thus, $b = c$ as desired. □

Remark. “There’s a result that says every finite integral domain is a field, but I don’t think we need that”

Definition 11.13. If $(R, +, \times)$ is a ring and $S \subseteq R$, we say that S is a subring if $(S, +, \times)$ is a ring with the same operations. (In particular, $(S, +) \leq (R, +)$.)

Definition 11.14. If $(R, +_R, \times_R), (S, +_S, \times_S)$ are rings, we say that $\varphi : R \rightarrow S$ is a ring homomorphism (or just homomorphism if “ring” is clear from the context) if for all $r_1, r_2 \in R$:

- $\varphi(r_1 +_R r_2) = \varphi(r_1) +_S \varphi(r_2)$
- $\varphi(r_1 \times_R r_2) = \varphi(r_1) \times_S \varphi(r_2)$

◀ Lecture 23 (2016–03–18)

Class Note

Midterm 2 will be in three weeks: April 8th or 11th.
There will be both group theory and ring theory.

Property 11.15 (Subring Criteria). Suppose $(R, +, \times)$ is a ring. Then $S \subseteq R$ is a subring iff it satisfies the following properties:

- Non-emptiness
- Closure under $+$
- Closure under $-$
- Closure under \times

Note that if we already know that $(S, +) \leq (R, +)$, then we only need to check closure under \times .

Example. $5\mathbb{Z}$ is a subring of \mathbb{Z} . Already checked $(5\mathbb{Z}, +) \leq (\mathbb{Z}, +)$. Closure under \times : Suppose $5m, 5n \in 5\mathbb{Z}$. Then $(5m)(5n) = 25mn = 5(5mn) \in 5\mathbb{Z}$.

Example. $\mathbb{Z}/5\mathbb{Z}$ is *not* a subring of \mathbb{Z} .

Note that it's not even a subgroup of \mathbb{Z} (with the operation of addition)

Example (Non-example). $\varphi : \mathbb{Z} \rightarrow \mathbb{Z}, z \mapsto 2z$. Is *not* a homomorphism. $\varphi(1 \times 1) = \varphi(1) = 2 \neq 4 = 2 \times 2 = \varphi(1) \times \varphi(1)$ (In fact the only two homomorphism $\mathbb{Z} \rightarrow \mathbb{Z}$ are $z \mapsto z, z \mapsto 0$)

Example. The map $\varphi : \mathbb{Z} \rightarrow \mathbb{Z}/3\mathbb{Z}, \varphi(z) = \bar{z} \pmod{3}$

Remark. Many authors demand that all rings have a multiplicative identity 1. Some of them demand that homomorphisms preserve the 1 ($\varphi(1_R) = 1_S$).

Definition 11.16. If $(R, +_R, \times_R), (S, +_S, \times_S)$ are rings, define the direct product $(R, +_R, \times_R) \times (S, +_S, \times_S)$ on the set $R \times S$ with $(r, s) + (r', s') = (r +_R r', s +_S s')$ $(r, s) \times (r', s') = (r \times_R r', s \times_S s')$

Example. $\mathbb{Z} \times \mathbb{Z}$ is a ring with $1 = (1, 1)$. The map $\varphi : \mathbb{Z} \rightarrow \mathbb{Z} \times \mathbb{Z}, \varphi(z) = (z, 0)$ is a ring homomorphism., but $\varphi(1) = (1, 0)$ is *not* the identity of $\mathbb{Z} \times \mathbb{Z}$.

Definition 11.17. $\varphi : R \rightarrow S$ is a ring homomorphism. Define the kernel $\text{Ker}(\varphi) \subseteq R$ by $r \in \text{Ker}(\varphi) \iff \varphi(r) = 0_S$

Proposition 11.18. Suppose $\varphi : R \rightarrow S$ is a ring homomorphism. Put $K = \text{Ker}(\varphi)$. Then:

(A) K is a subring of R

(B) $\forall a \in K, \forall r \in R (ar \in K \wedge ra \in K)$ (because $\varphi(ar) = \varphi(a)\varphi(r) = 0\varphi(r) = 0$)

Proof of (A). We already know that $(K, +) \leq (R, +)$. Thus, we only need to check closure under \times . Fix $a, b \in K$ sp $\varphi(a) = \varphi(b) = 0$. Want $ab \in K$ $\varphi(ab) = \varphi(a)\varphi(b) = 0 \cdot 0 = 0$. Thus $ab \in K$, as desired. \square

Definition 11.19. Let R be a ring, $I \subseteq R$. We say I is an ideal of R if:

(1) I is a subring of R

(2) $\forall r \in R (rI \subseteq I \wedge Ir \subseteq I)$ Where $rI = \{ra : a \in I\}$ and $Ir = \{ar : a \in I\}$

Proposition 11.20. If $\varphi : R \rightarrow S$ is a ring homomorphism then $\text{Ker}(\varphi)$ is an ideal of R .

Proposition 11.21 (Ideal Criteria). If $I \subseteq R$, R is a ring then I is an ideal iff:

(1) $I \neq \emptyset$

(2) $\forall a, b \in I (a + b \in I)$

(3) $\forall a \in I (-a \in I)$

(4) $\forall a \in I (\forall r \in R (ar \in I \wedge ra \in I))$

(Note that the last criterion is stronger than closure under \times in I .)

Example. $5\mathbb{Z}$ is an ideal of \mathbb{Z} .

We've already checked it's a subring. Fix arbitrary $5m \in 5\mathbb{Z}$ and $z \in \mathbb{Z}$. Then $(5m)z = 5(mz) \in 5\mathbb{Z}$. $z(5m) = 5(zm) \in 5\mathbb{Z}$. Thus, as our choices were arbitrary, $5\mathbb{Z}$ is an ideal

Example (Non-example). $R = 2 \times 2$ matrices with entries in \mathbb{Q} . $I = \{A \in R : \det A = 0\}$ Note that it satisfies the last ideal criterion. However, it is not closed under addition. $((\begin{smallmatrix} 1 & 0 \\ 0 & 0 \end{smallmatrix}) + (\begin{smallmatrix} 0 & 0 \\ 0 & 1 \end{smallmatrix})) = I_2$ and $\det I_2 \neq 0$)

Definition 11.22. If R is a ring, I is a subring, define $R/I = \{r + I : r \in R\}$ (this is exactly $(R, +)/(I, +)$).

Note $(r + I) + (s + I) = (r + s) + I$ is a well-defined abelian group operation on R/I .

Proposition 11.23. *If I is an ideal of R , the map $(r + I)(s + I) = rs + I$ is well-defined.*

Proof. Suppose $r + I = r' + I$ ($r - r' \in I$), $s + I = s' + I$ ($s - s' \in I$)

Want to show that $rs + I = r's' + I$ (i.e., $rs - r's' \in I$)

$$rs - r's' = rs + \underbrace{(-rs' + rs')}_{\in I} - r's' = \underbrace{r(s - s')}_{\in I} + \underbrace{(r - r')s'}_{\in I} \in I$$

□

◀ Lecture 24 (2016–03–21)

First, we're going to look at the ring-theoretic equivalent of the first isomorphism theorem.

Proposition 11.24. *Suppose R, S are rings, $\varphi : R \rightarrow S$ is a (ring) homomorphism. Then $\text{Im}(\varphi) = \{s \in S : \exists r \in R(\varphi(r) = s)\}$ is a subring of S .*

Proof. We already know that $(\varphi[R], +) \leq (S, +)$. So, $\varphi[R] \neq \emptyset$, and it's closed under $+$ and $-$.

Thus, we only need to check closure under \times . Fix $s_1, s_2 \in \varphi[R]$. Fix r_1, r_2 with $\varphi(r_i) = s_i$.

Want $s_1 s_2 \in \varphi[R]$.

Check $\varphi(r_1 r_2) = \varphi(r_1)\varphi(r_2) = s_1 s_2$. Thus, $s_1 s_2 \in \varphi[R]$. □

Definition 11.25. A (ring) isomorphism is a bijective (ring) homomorphism. If $\exists \varphi : R \rightarrow S$ an isomorphism, then we write $R \cong S$.

Theorem 11.26 (First Isomorphism Theorem for Rings). . *Suppose $\varphi : R \rightarrow S$ is a ring homomorphism. Then $R/\text{Ker}(\varphi) \cong \varphi[R]$.*

Proof. Put $K := \text{Ker}(\varphi)$ By First Isomorphism Theorem, the map $\Psi : R/K \rightarrow \text{Im}(\varphi)$ with $\Psi(r + K) = \varphi(r)$ is a bijective group homomorphism from $(R/K, +)$ to $(\text{Im}(\varphi), +)$. To verify that Ψ is a ring isomorphism, we just need it to preserve \times .

Fix $r_1 + K, r_2 + K \in R/K$. $\Psi((r_1 + K)(r_2 + K)) = \Psi(r_1 r_2 + K) = \varphi(r_1 r_2) = \varphi(r_1)\varphi(r_2) = \Psi(r_1 + K)\Psi(r_2 + K)$ □

Ideals are the same thing as kernels of homomorphisms.

More on ideals:

Proposition 11.27. *If $I, J \subseteq R$ are ideals, then $I \cap J$ is an ideal.*

Proof. See Homework 7. □

Proposition 11.28. *If $I, J \subseteq R$ are ideals, then $I + J = \{i + j : i \in I, j \in J\}$ is an ideal.*

Proof. We need to check our ideal criteria.

Non-zero: $0 = 0 + 0 \in I + J$.

Closed under $+$: Fix $i + j, i' + j' \in I + J$. Then $(i + j) + (i' + j') = (i + i') + (j + j') \in I + J$

Closed under $-$: Fix $i + j \in I + J$. Then $-(i + j) = (-i) + (-j) \in I + J$

Closed under \times by R : Fix $i + j \in I + J$ and $r \in R$. Then $r(i + j) = ri + rj \in I + J$ and $(i + j)r = ir + jr \in I + J$ □

Definition 11.29. Fix an $a \in R$, R a ring. Let (a) denote the smallest ideal containing a . I.e., (a) is the intersection of all ideals containing a . We call (a) the principal ideal generated by a .

If $A \subseteq R$ we denote by (A) the smallest ideal containing all elements of A . I.e.,

$$(A) = \bigcap_{\substack{I \text{ an ideal} \\ I \supseteq A}} I.$$

Remark. $I + J = I \cup J$

Proposition 11.30. *Suppose R is a commutative ring with a 1. Then $(a) = aR = \{ar : r \in R\}$. $(a) = R$ iff a is a unit.*

Proof. First show $aR \subseteq (a)$:

Fix $r \in R$. We know $a \in (a)$ So $ar \in (a)$. Hence $aR \subseteq (a)$.

Next show $aR \supseteq (a)$:

Since (a) is the “smallest” ideal containing a , it suffices to check that aR is an ideal containing a .

- (1) $(a \in aR)$: $a = a \cdot 1 \in aR$ (used that $1 \in R$).
- (2) $(aR \text{ is nonempty})$: $0 = a0 \in aR$
- (3) (Closure under $+$): $ar_1 + ar_2 = a(r_1 + r_2) \in aR$
- (4) (Closure under $-$): $-(ar) = a(-r) \in aR$
- (5) (Closure under \times by R): Fix $ar \in aR, s \in R$ First $(ar)s = a(rs) \in aR$. Second, $s(ar) = a(sr) \in aR$ (uses commutativity).

□

Remark. If R is not commutative but it still has a 1, we have if a is a unit then $(a) = R$. Otherwise, $(a) = \{\sum_{i=1}^k r_i a s_i : r_i, s_i \in R, k \in \mathbb{Z}^+\}$.

Remark. Warning: if R has no 1, then typically (a) is much bigger than aR (or RaR). For example, $R = 5\mathbb{Z}, a = 10, (a) = 10\mathbb{Z}$ but $aR = \{\dots, -100, -50, 0, 50, 100, \dots\}$.

Proposition 11.31. *Suppose R has a 1. $I \subseteq R$ is an ideal. Then $I = R$ iff I contains a unit. (So $(u) = R$ iff u is a unit).*

Proof. (\implies) : Assume $I = R$. Then $1 \in I$.

(\impliedby) : Suppose $u \in I$, u a unit. $\exists v \in R$ such that $uv = 1$. $1 = uv \in I$. Now fix $r \in R$. Then, $r = 1 \cdot r \in I$, so $I = R$ as desired. □

Corollary 11.31.1. *Suppose R is a commutative ring with $1 \neq 0$. Then R is a field if its only ideals are $(0) = \{0\}$ and R .*

Proof. (\implies) : Suppose R is a field and $I \subseteq R$ is an ideal. If $I = \{0\}$ then we’re done. Otherwise, $\exists r \neq 0$ with $r \in I$. Since r is a unit, $I = R$.

(\impliedby) : Suppose R has only $\{0\}$ and R for its ideals. Fix $0 \neq r \in R$. Want to show that r is a unit. Look at (r) . We know $r \in (r)$, so $r \neq 0$. Hence $(r) = R$. We also know that $(r) = rR$ by our assumptions along with proposition 11.31. So, $\exists s \in R$ such that $rs = 1$. We also have $sr = 1$. Thus r is a unit. □

◀ Lecture 25 (2016–03–23)

“When you’re a professor you don’t make mistakes, you make teachable moments.”

Definition 11.32. If $f : X \rightarrow Y, A \subseteq X, B \subseteq Y, f^{-1}[B] = f^{-1}(B) = \{x \in X : f(x) \in B\}$.

Proposition 11.33. *Suppose $\varphi : R \rightarrow S$ is a ring homomorphism with $B \subseteq S$ then,*

- (1) B is a subring of $S \implies \varphi^{-1}[B]$ is a subring of R .
 (2) B is an ideal of $S \implies \varphi^{-1}[B]$ is an ideal of R .

The proof is left as an exercise.

Proposition 11.34. *If $\varphi : R \rightarrow S$ is a surjective ring homomorphism, and $I \subseteq R$ is an ideal, then $\varphi[I] \subseteq S$ is an ideal of S .*

The proof is left as an exercise.

Definition 11.35. An ideal $I \subseteq R$ is a proper ideal if $I \neq R$.

Definition 11.36. An ideal $M \subseteq R$ is a maximal ideal if:

- (1) M is proper
 (2) If I is a proper ideal with $M \subseteq I$, then $I = M$.

Remark ((s)). • The zero ring $R = \{0\}$ has no proper ideals. Hence, it has no maximal ideal.

- If R is a commutative ring with a 1 , then R is a field iff $\{0\}$ is maximal.
- Fact/Axiom If R has a 1 then every proper ideal is contained in a maximal ideal. (This requires set theory). (We'll never actually use this in class probably).

Proposition 11.37. *Suppose R is a commutative ring with a 1 and $M \subseteq R$ is an ideal. Then M is maximal iff R/M is a field.*

Proof. (\implies)

Take M to be a maximal ideal. Since M is proper, $1 \notin M$. Hence in R/M we have $1 + M \neq 0 + M$.

Just need to show that the only ideals of R/M are $\{0 + M\}$ and R/M .

Suppose $I \subseteq R/M$ is an ideal. Fix $\varphi : R \rightarrow R/M$ to be the “quotient homomorphism” $\varphi(r) = r + M$.

$\varphi^{-1}[I]$ is an ideal in R . Moreover, if $m \in M$ then $\varphi(m) = m + M = 0 + M \in I$. So, $M \subseteq \varphi^{-1}[I]$. Now we can use maximality. Since M is maximal, there are two options for $\varphi^{-1}[I]$.

If $\varphi^{-1}[I] = M$ then $I = \{0 + M\}$.

If $\varphi^{-1}[I] = R$ then $I = R/M$.

Thus, R/M is a field.

(\Leftarrow) (Sketch) R/M is a field and $M \subseteq I \subseteq R$, with I an ideal. Look at $\varphi[I] = \{0 + M\}$ or R/M . (Full proof is left as an exercise). \square

Definition 11.38. R is a commutative ring with a 1 . An ideal $P \subseteq R$ is a prime ideal if:

- (1) P is proper
 (2) $\forall a, b \in R$, if $ab \in P$ then either $a \in P$ or $b \in P$

Proposition 11.39. *Let R be a commutative ring with a 1 , and $P \subseteq R$ is an ideal. Then P is prime iff R/P is an integral domain.*

Proof (Sketch). (\implies) P prime, want R/P to be an integral domain. Toward a contradiction, suppose that $r + P, s + P \neq 0 + P$ with $rs + P = (r + P)(s + P) = 0 + P$. I.e., $rs \in P$. As P is prime, one of r, s is in P . If $r \in P$ then $r + P = 0 + P$, contradiction. By symmetry, $s \in P$ is also a contradiction.

(\Leftarrow) Similar. \square

Corollary 11.39.1. *If R is a commutative ring with a 1 and $I \subseteq R$ is an ideal, then I is maximal $\implies I$ is prime.*

Proof. If R/I is a field, it's an integral domain. Then simply apply the previous proposition. \square

Example. Examples in \mathbb{Z} :

- Every ideal of \mathbb{Z} is principal.
- Every subgroup of $(\mathbb{Z}, +)$ has the form $n\mathbb{Z} = (n)$ for some $n \in \mathbb{N}_0$.
- Which of the (n) are prime? Answer: when n is prime or zero.
 If p is prime, then $z \in (p)$ iff $p|z$. So, $ab \in (p) \implies a \in (p)$ or $b \in (p)$. If $n \neq 0$ is composite, say $n = ab$. $ab \in (n)$, $a \notin (n)$, $b \notin (n)$.
- Which (n) are maximal?
 If (n) it is prime, so $n = 0$ or n is a prime number. (0) is not maximal (as $(0) \subsetneq (2) \subsetneq \mathbb{Z}$).
 If p is prime, then (p) is maximal. Why? Fix $a \notin (p)$. Show that $(\{p, a\}) = \mathbb{Z}$ (where $(\{p, a\})$ is the ideal generated by the set $\{p, a\}$). Since $\gcd(p, a) = 1$ fix $x, y \in \mathbb{Z}$ such that $px + ay = 1$. $px + ay$ is in any ideal containing both p and a . So, $1 \in (\{p, a\})$. Hence $(\{p, a\}) = \mathbb{Z}$.
- So in \mathbb{Z} , nonzero prime ideal \iff maximal ideal
- Bonus facts: Suppose $a, b, c \in \mathbb{Z}$ all non-zero.
 - If $(c) = (a) \cap (b) \iff \text{lcm}(a, b) = c$
 - $(c) = (a) + (b) \iff \gcd(a, b) = c$

◀ Lecture 26 (2016–03–25)

Class Note

Exam 2 will be on Monday April 11th
 (Also HW 9 is posted, don't forget they mention that R has a $1 \neq 0$)

Definition 11.40. If R is a commutative ring, $R[x] =$ polynomials with coefficients in $R = \sum_{i=0} a_i x^i$. (Note that if R has no 1 then x^0 doesn't exist so just write it as $a_0 + \sum_{i=1} a_i x^i$).

Property 11.41.

$$\left(\sum_{k=0}^m a_k x^k \right) \times \left(\sum_{k=0}^n b_k x^k \right) = \sum_{k=0}^{m+n} \left(\left(\sum_{i=0}^k a_i b_{k-i} \right) x^k \right)$$

Last time: we showed that given a commutative ring R with a 1, and an ideal $I \subseteq R$.

- I is maximal $\iff R/I$ is a field.
- I is prime $\iff R/I$ is an ID.

The first point generalizes $(\mathbb{Z}/p\mathbb{Z})$ is a field for prime p . The “other” way to make a field out of \mathbb{Z} is “ \mathbb{Q} .”

12. Fields of Fractions

Theorem 12.1. *Suppose $R \neq \{0\}$ is a commutative ring with no zero-divisors. Then there is a field Q with a subring $R' \subseteq Q$ with $R \cong R'$*

Proof (sketchy).¹

Put $D := R \setminus \{0\}$. D satisfies:

- $D \neq \emptyset$ (because $R \neq \{0\}$)
- $0 \notin D$
- D contains no zero-divisors
- $\forall a, b \in D (ab \in D)$

D will be the set of valid “denominators” in our construction.

Formally define $F = R \times D = \{(r, d) : r \in R, d \in D\}$.

Think of (r, d) as “ $\frac{r}{d}$ ”.

Define \approx on F by $(r, d) \approx (s, e) \iff re = sd$.

Exercise: Prove that \approx is an equivalence relation.

Denote by Q the set F/\approx of equivalence classes of \approx .

Write $\frac{r}{d}$ for the equivalence class $[(r, d)]_\approx$.

So, $\frac{r}{d} = \frac{s}{e} \iff (r, d) \approx (s, e) \iff re = sd$.

Formally “define” addition and multiplication in Q by

$$\frac{a}{b} + \frac{c}{d} = \frac{ad + cb}{bd} \qquad \frac{a}{b} \times \frac{c}{d} = \frac{ac}{bd}$$

Note that $bd \in D$ because D is closed under multiplication.

Claim (1). Addition in Q is well-defined

Proof that addition is well defined (C1). We need to show if $\frac{a}{b} = \frac{a'}{b'}$, $\frac{c}{d} = \frac{c'}{d'}$ (i.e., $ab' = a'b$ and $cd' = c'd$), then $\frac{a}{b} + \frac{c}{d} = \frac{a'}{b'} + \frac{c'}{d'}$. I.e., $\frac{ad+cb}{bd} = \frac{a'd'+c'b'}{b'd'}$, i.e., $(ad + cb)b'd' = (a'd' + c'b')bd$.

$$\begin{aligned} (ad + cb)b'd' &= adb'd' + cbb'd' \\ &= (ab')dd' + (cd')bb' \\ &= (a'b)dd' + (c'd)bb' \\ &= a'd'bd + c'b'bd \\ &= (a'd' + c'b')bd \end{aligned}$$

□

Claim (2). Multiplication in Q is well-defined

¹Side note to the reader: if you’ve ever constructed the rationals from the integers before, we’ll be following approximately that sort of procedure.

Proof that multiplication is well defined (C2). The proof is left as an exercise to the reader. \square (C2)

Claim (3). $(Q, +, \times)$ is a ring

Proof of Claim 3. $(Q, +)$ is an abelian group as we already know that $+$ is commutative and associative.

Subclaim $\forall d, d' \in D, \frac{0}{d} = \frac{0}{d'}$.

Pf (subclaim) $0d' = 0 = 0d$ \square

Let 0_Q denote the unique element of Q of the form $\frac{0}{d}$ for $d \in D$. Check: $\frac{0}{d} + \frac{a}{b} = \frac{0b+ad}{db} \stackrel{?}{=} \frac{a}{b}$

Note that $adb = abd$, so the final equality holds.

Thus, $\frac{0}{d} = 0_Q$ is the additive identity.

We assert that $-\left(\frac{a}{b}\right) = \frac{-a}{b}$.

Next, we show that \times is an associative binary operator on Q and that the distributive property holds.

Fire Alarm

Unfortunately at this point, the fire alarm went off. It is left to the reader to complete the proof or look up the remainder of it in the textbook.

\square

\square (Thm)

◀ **Lecture 27 (2016–03–28)**

13. Polynomials Over Integral Domains

First, we're going to focus on polynomials over fields. Typical polynomial in $R[x]$ looks like $p(x) = \sum_k^n a_k x^k$ with $a_k \in R$ and $n \in \mathbb{N}_0$.

Questions: Can we factor them? Uniquely? Can we “solve” polynomial equations, etc.

Definition 13.1.

- Each a_k is a coefficient
- Each $a_k x^k$ is a term
- The largest k with $a_k \neq 0$ (if it exists) is called the degree of $p(x)$ (denoted $\deg p$)
- If all $a_k = 0$ we leave the degree undefined (but we can consider it to be $-\infty$ for various reasons that “we’re not going to get into”)
- If $\deg p = n$ we call $a_n, a_n x^n$ the leading coefficient and the leading term, respectively.
- If the leading coefficient is 1, we say p is monic.

Proposition 13.2. *Let R be an integral domain, $p(x), q(x) \in R[x]$ both non-zero. Then, $\deg(p(x)q(x)) = \deg p + \deg q$.*

Proof. Suppose $\deg p = m, \deg q = n$. Apply the definition of multiplication. The leading term of the products is therefore $a_m b_n x^{m+n}$. ($a_m b_n \neq 0$ because R is an integral domain). \square

Corollary 13.2.1. *R is an integral domain.*

- (1) *Units of $R[x]$ are exactly the units of R (viewed as a degree 0 polynomial.)*
- (2) *$R[x]$ is an ID.*

Proof.

- (1) Suppose p is a unit. Fix $q \in R[x]$ such that $p(x)q(x) = 1$. $\deg(1) = 0$. So, $\deg(pq) = \deg(p) + \deg(q) = 0$. Hence, $\deg p = \deg q = 0$. Thus, $p(x) = a_0, q(x) = b_0$. $a_0 b_0 = 1$, so a_0, b_0 are units in R .
- (2) Analogous.

\square

Theorem 13.3 (Division Algorithm for Polynomials over fields). *Suppose F is a field, $a(x), b(x) \in F[x]$ with $b(x) \neq 0$. Then, there are $q(x), r(x) \in F[x]$ such that*

- $a(x) = q(x)b(x) + r(x)$
- $r = 0$ or $\deg r < \deg b$

(Also q and r are unique, proof left as an exercise.)

Proof. We proceed by induction on $m = \deg a$.

If $a = 0$, then $q = r = 0$.

Suppose the theorem is true for all a' (with the same b) with $\deg(a') < m$.

Case 1 ($\deg a < \deg b$):

$$a = 0b + a$$

Case 2 ($\deg a \geq \deg b$):

Denote by n the degree of b . Fix leading terms $a_m x^m$ of $a(x)$ and $b_n x^n$ of $b(x)$.

Define $a'(x) = a(x) - \frac{a_m}{b_n} x^{m-n} b(x)$.

Claim. $\deg a' < \deg a$ (or $a' = 0$)

Proof (Claim). Coefficients above m are 0. What about the coefficient of x^m ? It equals $a_m - \frac{a_m}{b_n} b_n = 0$.

So, $\deg(a') < n$ (or $a' = 0$) □

So, by induction, $\exists q', r' \in F[x]$ such that

- $a'(x) = q'(x)b(x) + r'(x)$
- $r' = 0$ or $\deg r' < \deg b$

We know

$$\begin{aligned} a(x) &= a'(x) + \frac{a_m}{b_n} x^{m-n} b(x) \\ &= q'(x)b(x) + r'(x) + \frac{a_m}{b_n} x^{m-n} b(x) \\ &= \underbrace{\left(q'(x) + \frac{a_m}{b_n} x^{m-n} \right)}_{q(x)} b(x) + r'(x) \end{aligned}$$

□

We needed F to be a field. Consider $a(x) = 3x + 1, b(x) = 2$ in $\mathbb{Z}[x]$.

Definition 13.4. An ID R is a Euclidean domain (ED) if there is a function $N : R \rightarrow \mathbb{N}$ such that $\forall a, b \in R, b \neq 0 \exists q, r \in R$ with

- $a = qb + r$
- $r = 0$ or $N(r) < N(b)$

Notation. N (as described above) is called a norm.

- q is the quotient
- r is the remainder

Example.

- $R = \mathbb{Z}, N(z) = \text{abs } z$
- $F[x]$ with F a field, $N(p) = \deg p$
- F a field, N any function.

Definition 13.5. An ID R , is a principal ideal domain (PID) if every ideal is principal (i.e., $I \subseteq R$ an ideal $\implies \exists a \in R (I = (a) = aR)$)

Proposition 13.6. *Every Euclidean domain is a principal ideal domain.*

Proof. Fix ED R , $I \subseteq R$ an ideal. If $I = \{0\}$ then $I = (0)$. If $I \neq \{0\}$, fix $a := \arg \min_{a \in I \setminus \{0\}} N(a)$.

Claim. $I = (a)$

Proof of Claim. $(a) \subseteq I$, need $I \subseteq (a)$ Fix $s \in I$. By ED, $\exists q, r \in R$ such that $s = qa + r$ with $N(r) < N(a)$ or $r = 0$. $r = s - qa \in I$. Thus, as a was minimal, $r = 0$. Thus $s = qa \in (a)$ \square

 \square

◀ Lecture 28 (2016–03–30)

Remark. R commutative ring, $a \in R$.

The map $eval_a : R[x] \rightarrow R, p(x) \mapsto p(a)$ is a homomorphism of rings.

Let's go back to EDs. EDs are PIDs in particular $F[x]$ with F a field.

Example. $\mathbb{Z}[x]$ is NOT a PID. We'll show this by contradiction.

Look at $I = \{p(x) \in \mathbb{Z}[x] : \text{constant term is even}\}$ $I = eval_0^{-1}(2\mathbb{Z})$ hence an ideal. Suppose I were principal, say $I = (p(x))$. First $2 \in I$ (constant 2 polynomial. 2 is a multiple of $p(x)$) $p(x)$ cannot be ± 1 as otherwise $(p(x)) = \mathbb{Z}[x]$ so $p(x) = \pm 2$. We also know $x \in I$. But there is no $q(x)$ such that $x = 2q(x)$. Thus ± 2 can't generate it. Thus I is not principal.

Variant: if $R[x]$ is a PID, then R is a field.

Definition 13.7. Let R be a commutative ring and $a, b \in R$ we say a divides b , or $a|b$, if $\exists r \in R (ar = b)$.

Proposition 13.8. For $a, b \in R$, R commutative with a $1 \neq 0$, the following are equal:

- (1) $a|b$
- (2) $b \in (a)$
- (3) $(b) \subseteq (a)$

Proof. $(1 \implies 2)$:

$a|b \exists r \in R ar = b, ar \in I$ for all ideals I with $a \in I$. Hence $b = ar \in (a)$.

$(2 \implies 3)$:

(a) is an ideal, it contains b . (b) is the smallest such ideal. Thus $(b) \subseteq (a)$.

$(3 \implies 1)$:

$(a) = aR = \{ar : r \in R\}$. $(b) \subseteq (a), b \in (a)$, so $b = ar$ for some $r \in R$. \square

Definition 13.9. We say $a, b \in R$ (commutative ring with a 1) are commensurate if $(a) = (b)$.

(By proposition, $a|b$ and $b|a$)

Proposition 13.10. Suppose R is an ID. Then, $a, b \in R$ are commensurate iff there exists a unit u such that $a = ub$.

Proof. (Commensurate $\implies \exists u$):

Fix $r, s \in R$ such that $ar = b, bs = a$. So $(ar)s = a \implies a(rs) = a$ So, $a(rs - 1) = 0$

If $a = 0$ then $b = 0$ so $0 = 10$. Otherwise, $rs - 1 = 0 \implies rs = 1$ so s is a unit.

$(\exists u \implies \text{commensurate})$:

Suppose $a = ub, b|a$ u a unit, $\exists v \in R vu = uv = 1$. Hence $va = vub = 1b = b$ Thus $a|b$. Hence a, b are commensurate. \square

Definition 13.11. Work in commutative ring R with a 1 . We say d is a gcd of the nonzero elements $a, b \in R$ if

- (1) $d|a$ and $d|b$
- (2) If $c|a$ and $c|b$ then $c|d$

Note that if d and d' are both gcds of the same pair a, b . $d|d'$ and $d'|d$, so d and d' are commensurate and thus, in an ID, $\exists u$ unit such that $d = ud'$.

Theorem 13.12. *If R is a principal ideal domain, then gcds exists. (If $a, b \in R$ nonzero, $\exists d \in R$ such that d is a gcd of a, b .) Moreover, this gcd d has the form $d = ax + by$ for some $x, y \in R$.*

Proof. Note that it is enough to show that there exists a gcd of the form $ax + by$

Let I be the ideal $(a) + (b) = \{r + s : r \in (a), s \in (b)\}$.

This ideal is principal as R is a PID, so say $I = (d)$.

$d \in (d)$ so $d = r + s$ for some $r \in (a), s \in (b)$, so $d = ax + by$ for some $x, y \in R$.

Claim. d is a gcd of a, b .

Proof. $a \in (a)$, hence $a = a + 0 \in (a) + (b) = I$. $a \in (d)$, so $d|a$. Similarly, $d|b$. \square (Claim)

Next, suppose $c \in R$ such that $c|a$ and $c|b$.

Fix $r, s \in R$ such that $a = rc, b = sc$. $a \in (c)$, $b \in (c)$. Thus, $d = ax + by \in (c)$ so $c|d$. \square (Thm)

In particular, polynomials, over a field always have gcds.

Next time we'll prove polynomials admit unique factorizations.

◀ Lecture 29 (2016-04-01)

Class Note

Homework 10 is now due Friday April 8 at any time.

Midterm 2 will still be on Monday April 11.

No homework will be due exam week.

Remark. “Commensurate” also called “associate”. Sometimes we'll even write $a \sim b$.

Story so far:

Fields \subseteq Euclidean domains \subseteq Principal ideal domains \subseteq Integral domains

Proposition 13.13. *Suppose R is a PID and $I \subseteq R$ is a nonzero ideal. Then, I is a prime ideal iff I is a maximal ideal.*

Proof. Maximal \implies Prime (R commutative with a $1 \neq 0$) was already done.

Next we want to show Prime \implies Maximal. So suppose I is a nonzero prime. Pick a generator $p \neq 0$ with $I = (p)$. Now suppose J is another ideal with $I \subseteq J \subseteq R$. We want to prove that $J = I$ or $J = R$.

Fix a generator $a \neq 0$ for J so that $(a) = J$.

$(p) \subseteq (a)$ so $a|p$. Fix $r \in R$ such that $p = ar$. $ar \in (p) = I$. As I is prime, either $a \in I$, or $r \in I$.

Case 1 ($a \in I$):

This means $(a) \subseteq I$. So $J \subseteq I$, thus $J = I$

Case 2 ($r \in I$):

$r \in (p)$ so $p|r$. Say $r = bp$ for some $b \in R$. $p = ar = abp$. $p - abp = 0$, $(1 - ab)p = 0$. Thus, $1 - ab = 0$ or $1 = ab \in (a)$. Hence $J = (a) = R$

□

What does (maximal = prime) say about ring *elements*?

Definition 13.14. Let R be an ID. We say $p \in R$ is prime when:

- $p \neq 0$
- p is not a unit
- $\forall a, b \in R$ if $p|ab$ then $p|a$ or $p|b$.

Exercise. R is an ID. Prove that $p \neq 0$ is prime iff (p) is a prime ideal.

R an ID.

Definition 13.15. We say that $r = ab$ is a proper factorization if neither a nor b is a unit.

Definition 13.16. We say $r \in R$ is irreducible if:

- $r \neq 0$
- r is not a unit
- r admits no proper factorization. ($\forall a, b \in R$, if $ab = r$ then either a or b is a unit)

Proposition 13.17. Suppose $r \neq 0$ and $r = ab$ is a proper factorization of r . Then $(r) \subseteq (a) \subseteq R$ and $(a) \neq (r)$, $(a) \neq R$. Particularly, (r) is not maximal.

Proof. $(r) \subseteq (a) \subseteq R$ is clear since $a|r$.

$(a) \neq (r)$: Towards a contradiction, suppose $(a) = (r)$. So, a, r are associates. Thus, as R is an ID, \exists a unit $u \in R$ ($r = au$). $a(u - b) = au - ab = r - r = 0$ $a \neq 0$ since $ab = r \neq 0$. So $u - b = 0$, so $b = u$. This is a contradiction since b is not a unit.

$(a) \neq R$: $(a) = R$ would imply a is a unit. But it isn't. □(prop)

Proposition 13.18. In a PID $r \neq 0$ is irreducible iff (r) is a maximal ideal.

Proof. Maximal \implies Irreducible:

Note that (r) maximal means $(r) \neq R$. so r is not a unit. Now suppose r has a proper factorization $r = ab$. We would have $(r) \subsetneq (a) \subsetneq R$. This would contradict maximality. Thus, r has no proper factorization, so it is irreducible.

Irreducible \implies Maximal:

Suppose r is irreducible. Towards a contradiction suppose (r) is not maximal. I.e., \exists an ideal $I \subseteq R$ with $(r) \subsetneq I \subsetneq R$. Since R is a PID, fix $a \in R$ with $(a) = I$. Check: any factorization $r = ab$ is proper. This contradicts irreducibility. Hence $r = ab$ is proper. □

Corollary 13.18.1. In a PID, an element r is prime iff r is irreducible.

Proof. Look at (r) . □

Looking back at proving unique factorization of integers, we see that we used primeness coinciding with irreducibility.

Definition 13.19. A ring R is a Noetherian Ring if there is no strictly increasing sequence $I_0 \subsetneq I_1 \subsetneq I_2 \subsetneq \dots$ of ideals.

Proposition 13.20. If R is a PID, then R is Noetherian.

Proof. Towards a contradiction, say we have a sequence $I_0 \subsetneq I_1 \subsetneq I_2 \subsetneq \dots$ of ideals.

On Homework: $I = \bigcup_{n \in \mathbb{N}} I_n$ is also an ideal. R is a PID, so I is principal, so $I = (c)$ for some $c \in I = \bigcup_{n \in \mathbb{N}} I_n$. Fix n such that $c \in I_n$. So $(c) \subseteq I_n$. But $I_{n+1} \subseteq \bigcup_{n \in \mathbb{N}} I_n = (c) \subseteq I_n$. Hence $I_n = I_{n+1}$. This is a contradiction, so R is Noetherian. \square

◀ Lecture 30 (2016–04–04)

Class Note

This lecture is the cutoff for midterm 2 material. No material after this lecture will be on the exam.

Digression

A tree is a set of nodes (or vertices) with a binary relation “is a child of” such that

- There is a special root node that is the
- Every node but the root node is the child of exactly one other node. (The root is not a child.)
- Every node is a descendant of the root node

Definition 13.21. y is a descendant of x if:

- $y = x$ or
- y is a child of x or
- y is a child of a child of x or
- \dots

Write $\text{desc}(x)$ for the set of descendants of x .

Definition 13.22. A node is terminal (or is a leaf) if $\text{desc}(x) = \{x\}$

Definition 13.23. A branch through a tree is a sequence $(x_n)_{n \in \mathbb{N}}$ such that

- x_0 is the root
- x_{n+1} is a child of x_n

Definition 13.24. A tree is locally finite if every node has finitely many (immediate) children.

Note that a locally finite tree can still have an infinite number of nodes in total.

Lemma 13.24.1 (König). *Suppose that T is a locally finite tree with infinitely many nodes. Then T has a branch*

Proof. Note that if x is a node with $\text{desc}(x)$ infinite, then x has a child y with $\text{desc}(y)$ infinite.

$$\text{desc}(x) = \{x\} \cup \bigcup_{i=1}^n \text{desc}(y_i)$$

where y_i are the children of x . If all of the $\text{desc}(y_i)$ were finite, $\text{desc}(x)$ would also be finite, so there must be at least one y_i with infinitely many descendants.

Note: The root (by hypothesis) has infinitely many descendants. We build a branch as follows: $x_0 = \text{root}$. Build x_{n+1} a child of x_n such that $\text{desc}(x_{n+1})$ is infinite. \square

So how are we going to use König’s lemma? Unique factorization!

Theorem 13.25 (Unique Factorization). *Suppose that R is a Principal Ideal Domain, and $r \in R$ is a non-zero element that is not a unit. Then:*

- (1) *There exists a sequence p_1, \dots, p_m of irreducibles in R such that $r = p_1 p_2 \dots p_m$*
- (2) *This factorization is “unique up to associates” i.e., if $r = q_1 \dots q_n$ is another factorization into irreducibles, then $m = n$ and $\exists \sigma \in S_n$ such that $p_i \sim q_{\sigma(i)}$*

Proof.

- (1) Build a “factorization tree” T with a root r such that:
 - If a node is reducible, it has two children which form a proper factorization
 - If a node is irreducible, it is terminal.

Claim. T has no branch.

Proof of claim. If T had a branch, $x_0 = r, x_1, \dots$ then $\forall n \in \mathbb{N}, (x_n) \subsetneq (x_{n+1})$. So $(x_0) \subsetneq (x_1) \subsetneq (x_2) \subsetneq \dots$, is a strictly increasing sequence of ideals of R , contradicting Noetherianness. \square (Claim)

Thus, by König’s Lemma, the tree is finite. So, the tree lies above some finite level. From here, we see r is the product of the irreducibles on the terminal nodes.

- (2) Suppose $r = p_1 p_2 \dots p_m = q_1 \dots q_n$ are factorizations into irreducibles. (Recall that in PIDs, irreducibles \equiv primes.)

We’ll proceed by induction on m . (The reader can check $m = 1$.)

We know that $p_m | q_1 \dots q_n$ and p_m is prime, so $\exists i \leq n$ such that $p_m | q_i$.

Say that $p_m u = q_i$ for $u \in P$. Note that u is a unit. Thus, $p_m \sim q_i$. Also, we have $p_1 p_2 \dots p_m = q_1 \dots \underbrace{(p_m u)}_{=q_i} \dots q_n$. Thus, $p_1 p_2 \dots p_{m-1} = \underbrace{u q_1 \dots q_{i-1} q_{i+1} \dots q_n}_{:=q'_1}$.

Now that we’ve reduced m by 1, induction handles the rest. \square (Thm.)

Definition 13.26. A UFD (Unique Factorization Domain) is an ID satisfying Unique Factorization.

Remark. In UFDs, primeness \equiv irreducibility, in IDs, primeness \implies irreducibility. Thus, so far,

$$\text{Fields} \subset \text{EDs} \subset \text{PIDs} \subset \text{UFDs} \subset \text{IDs}$$

Corollary 13.26.1. *If F is a field, then $F[x]$ is a UFD. Moreover, if $p(x) \in F[x]$ is monic, there is a unique factorization of $p(x)$ into irreducible monic polynomials.*

◀ **Lecture 31 (2016–04–06)**

Gaussian Integers

$\mathbb{Z}[i]$, the ring of Gaussian integers.

First, a refresher regarding the complex numbers (\mathbb{C}):

Basic properties of $\mathbb{C} = \{a + bi : a, b \in \mathbb{R}\}$, $i^2 = -1 \cong \mathbb{R}[x]/(x^2 + 1)$ (exercise).

We’ll use greek letters to denote complex numbers.

- \mathbb{C} is a commutative ring with a 1 (in particular, an ID)
- \mathbb{C} is a Field
- Conjugation $\alpha \mapsto \bar{\alpha}$ where $\overline{a + bi} = a - bi$
- Note that $\overline{\alpha\beta} = \bar{\alpha}\bar{\beta}$ and $\overline{\alpha + \beta} = \bar{\alpha} + \bar{\beta}$, so conjugation is a ring homomorphism from $\mathbb{C} \rightarrow \mathbb{C}$.

- “Norm” function $N : \mathbb{C} \rightarrow \mathbb{R}$, $N(\alpha) = \alpha\bar{\alpha}$ so $N(a + bi) = a^2 + b^2$
- $N(\alpha\beta) = N(\alpha)N(\beta)$

Definition 13.27. $\mathbb{Z}[i] \subset \mathbb{C}$ is the subring $\{a + bi : a, b \in \mathbb{Z}\}$. Called the Gaussian Integers.

Facts about $\mathbb{Z}[i]$:

- It is a commutative ring with a 1
- It is an integral domain
- $(\mathbb{Z}[i])^\times = \{\pm 1, \pm i\}$ (the set of units)
(Pf sketch: If u is a unit then $1 = N(1) = N(u^{-1}u) = N(u^{-1})N(u)$, then case)
- It is a Euclidean Domain with the norm N .

Proposition 13.28. $\mathbb{Z}[i]$ is a Euclidean Domain with the norm N . $N(a + bi) = a^2 + b^2$

Proof. Fix $\alpha, \beta \in \mathbb{Z}[i]$ with $\beta \neq 0$. Want $\chi, \rho \in \mathbb{Z}[i]$ such that $\alpha = \chi\beta + \rho$ and $N(\rho) < N(\beta)$ (or $\rho = 0$)

Let's look at all possible numbers $\{\chi\beta : \chi \in \mathbb{Z}[i]\} = \mathbb{Z}[i]\beta$.

If $\beta = a + bi$, then $i\beta = -b + ai$. (In geometric terms, this equates to rotating the vector β 90° CCW)

$N(\alpha - \chi\beta) < N(\beta)$ So, $\alpha = \chi\beta + \rho$ □

Corollary 13.28.1. Since $\mathbb{Z}[i]$ is a Euclidean Domain, it is also a PID and a UFD, so the set of primes is equal to the set of irreducibles.

Question: What are the irreducibles?

Let's try prime $p \in \mathbb{Z}$. $2 = (1 + i)(1 - i)$, $5 = (2 + i)(2 - i)$, 7 ✓

Proposition 13.29. If $p \in \mathbb{Z}$ is prime (in \mathbb{Z}) and $p \equiv 3 \pmod{4}$ then p is still prime (irreducible) in $\mathbb{Z}[i]$.

Proof. Towards a contradiction, suppose that $p = \alpha\beta$ for non-units $\alpha, \beta \in \mathbb{Z}[i]$.

$N(p) = p^2 = N(\alpha)N(\beta)$. Also, $N(\alpha), N(\beta) \neq 1$. So, $N(\alpha) = N(\beta) = p$. Say $\alpha = a + bi$. So $p = N(\alpha) = a^2 + b^2$. Hence $a^2 + b^2 \equiv 3 \pmod{4}$, which is a contradiction. The remainder of the proof is homework. □

Next goal: show all other primes are reducible.

Proposition 13.30. Suppose p is prime in \mathbb{Z} , $p \equiv 1 \pmod{4}$. Then $\exists n \in \mathbb{N}$ such that $n^2 \equiv -1 \pmod{p}$.

Proof. We work in the field $\mathbb{F} = (\mathbb{Z}/p\mathbb{Z}, +, \times)$ and the multiplicative group $G = (\mathbb{F} \setminus \{0\}, \times)$. So $|G| = p - 1 \equiv 0 \pmod{4}$ So $4 = 2^2$ divides $|G|$ By Sylow, $\exists H \leq G$ with $|H| = 4$. So $\forall h \in H$, $|h| \in \{1, 2, 4\}$

Claim. If $g^2 = 1$ then $g = \pm 1$

Proof of claim. Fix such a g , work in \mathbb{F} . $(g + 1)(g - 1) = g^2 - 1 = 0$. Thus, $g = \pm 1$. □

Hence, $\exists h \in H$ of order 4 $h^2 \neq 1$ but $(h^2)^2 = h^4 = 1$. So $h^2 = -1$ in \mathbb{F} . Now fix $n \in \mathbb{N}$ such that $n \equiv h \pmod{p}$. Then $n^2 \equiv -1 \pmod{p}$. □

Proposition 13.31. Suppose p is prime (in \mathbb{Z}) and $p \equiv 1 \pmod{4}$. Then p is not prime (irreducible) in $\mathbb{Z}[i]$

Proof. Fix $n \in \mathbb{N}$ such that $n^2 \equiv -1 \pmod{p}$ (i.e., $p \mid (n^2 + 1)$). Factor $1 + n^2 = (1 + ni)(1 - ni)$ so $p \mid (1 + ni)(1 - ni)$ (in $\mathbb{Z}[i]$). Suppose towards a contradiction that p is prime. Then p divides a factor. Say $p \mid (1 + ni)$.

Claim. $p \mid (1 - ni)$ as well.

Proof. We know that $p = \bar{p} \overline{(1 + ni)} = (1 - ni)$. □

Hence, $p \mid (1 + \pm ni)$. So $p \mid (1 + ni) + (1 - ni)$, so $p \mid 2$, contradiction ($N(p) > N(2)$) □

Theorem 13.32 (Fermat). p prime, $p \equiv 1 \pmod{4}$. Then, $\exists a, b \in \mathbb{N}$ such that $a^2 + b^2 = p$ and a, b are unique.

◀ Lecture 32 (2016–04–08)

Suppose R is an ID. When is $R[x]$ a UFD? It is when R is a field. If $R[x]$ is a UFD. R “ \subseteq ” $R[x]$ as constant polynomials. The units of $R[x]$ are the units of R . So $R[x]$ is a UFD $\implies R$ is a UFD.

Theorem 13.33. If R is a UFD, so is $R[x]$.

Corollary 13.33.1. \mathbb{Z} is a UFD, so $\mathbb{Z}[x]$ is a UFD. Also, $(\mathbb{Z}[x])[y] = \mathbb{Z}[x, y]$ is a UFD.

Some basic facts about UFDs:

Fix UFD R with field of fractions F (Think $R = \mathbb{Z}, F = \mathbb{Q}$). Abuse notation and say $R \subseteq F$ with $r = \frac{r}{1}$.

Facts (when we say $\gcd = 1$, we mean any unit):

- (1) If $a, b \in R$ nonzero, then $\gcd(a, b)$ exists (collect common irreducible factors). Similarly, $\gcd(a, b, c) = \gcd(a, \gcd(b, c)) = \gcd(\gcd(a, b), c)$
- (2) In the field of fractions F , we can represent an $f \in F$ as $\frac{a}{b}$ with $\gcd(a, b) = 1$.
- (3) Given $f_1, \dots, f_n \in F$ nonzero, can find $d \in R$ such that $\gcd(d, df_1, df_2, \dots, df_n) = 1$ and each $df_1, \dots, df_n \in R$ (d is the lowest common denominator).
- (4) If $c \mid ab$ and $\gcd(a, c) = 1$ then $c \mid b$.

Example (Annoying example). $2x + 4$ is irreducible in $\mathbb{Q}[x]$.

But, $2x + 4$ is reducible in $\mathbb{Z}[x]$ as $2(x + 2)$ is a proper factorization (as 2 is not a unit in \mathbb{Z})

Next, some definitions. Let $f(x) = \sum_{i=0}^n a_i x^i \in R[x]$.

Definition 13.34. We define the content of f $c(f)$, to be $\gcd\{a_0, a_1, \dots, a_n\}$.

For example, $c(2x + 4) = 2$

Definition 13.35. If $c(f) = 1$, we say f is primitive.

Lemma 13.35.1 (Gauss). If R is a UFD and $f, g \in R[x]$ are primitive, then fg is also primitive.

Proof. Towards a contradiction, suppose $c(fg)$ is not a unit. Fix any irreducible $p \in R$ with $p \mid c(fg)$. Let $P = (p) = pR$. p irreducible $\implies p$ prime (because UFD). Thus P is a prime ideal. So, R/P is an ID, hence so too is $(R/P)[x]$.

Claim. If $\varphi : R \rightarrow S$ is a ring homomorphism, then $\psi : R[x] \rightarrow S[x]$ defined by $\psi(a_n x^n + \dots + a_0) = \varphi(a_n) x^n + \dots + \varphi(a_0)$

The proof is left to the reader.

Build $\psi : R[x] \rightarrow (R/P)[x]$ by $\psi(a_n x^n + \dots + a_n) = (a_n + P)x^n + \dots + (a_0 + P)$. By the previous claim, ψ is a ring homomorphism. Note $\psi(f)\psi(g) = \psi(fg) = (0 + P)$ (the constant zero polynomial in $(R/P)[x]$).

Thus, $\psi(f) = 0 + P$ or $\psi(g) = 0 + P$. If $\psi(f) = 0$, then $p|c(f)$ contradicts f being primitive. The same argument applies to g . \square (Lem.)

Corollary 13.35.1. *For $f, g \in R[x]$, $c(fg) = c(f)c(g)$.*

Proof. Fix primitive $f_0, g_0 \in R[x]$ such that $f = c(f)f_0$ and $g = c(g)g_0$. Then,

$$fg = c(f)f_0c(g)g_0 = \underbrace{c(f)c(g)}_{\in R} \cdot \underbrace{f_0g_0}_{\substack{\in R[x] \\ \text{primitive}}}$$

\square (Cor.)

Proposition 13.36. *If $f \in R[x]$ is primitive, f is reducible in $R[x]$ iff f is reducible in $F[x]$.*

Proof. $R[x]$ reducible $\implies F[x]$ reducible.

If $f(x) = g(x)h(x)$ is a proper factorization in $R[x]$. Then neither g nor h is constant. So, both have degree at least 1. Thus, neither is a unit in $F[x]$.

$F[x]$ reducible $\implies R[x]$ reducible.

If $f(x) = g(x)h(x)$ is a proper factorization in $F[x]$. We may take $\tilde{g}, \tilde{h} \in R[x]$ such that $f = \tilde{g}\tilde{h}$ and $g \sim \tilde{g}$ and $h \sim \tilde{h}$ in $F[x]$

The remainder of the proof will be typed up soon.

\square

◀ Lecture 33 (2016–04–13)

Intuition: We want to show that if R is a UFD, then $R[x]$ is a UFD. We're going to do this by "sandwiching" $R[x]$ between two UFDs as $R \subset R[x] \subset F[x]$, where F is the field of fractions of R .

Criteria for determining whether polynomials are irreducible.

Let F field, $a \in F$, $f \in F[x]$. As $f = (x - a)q + r$ for a unique q, r . Substituting $x = a$, $r = f(a)$. In particular $f(a) = 0 \iff x - a$ divides f in $F[x]$.

The units of $F[x]$ are the non-zero constants.

Polynomials of degree 1 are irreducible. (Might not be all of them). In any ID, an associate of an irreducible element is also irreducible. Similarly, associates of prime elements are also prime.

As associate-ness is an equivalence relation, we'll choose the irreducible elements as equivalence class representatives.

If $cx + d$, $c, d \in R$, $c \neq 0$ is a degree 1 polynomial, there is a unique monic associate $c^{-1}(cx + d) = x + dc^{-1}$

Proposition 13.37. *If F is a field, $f \in F[x]$ and $2 \leq \deg(f) \leq 3$, f is irreducible in $F[x]$ $\iff f$ has no roots in F .*

Proof. If f is irreducible, then it has no roots, because a is a root $\implies (x - a)|f \implies f = (x - a)g$ with $\deg(g) = \deg(f) - 1 > 0$

If $f = gh$, then $\deg(f) = \deg(g) + \deg(h)$. If g, h are not units, $\deg(g) > 0, \deg(h) > 0$, so $\deg(f) \geq 2$ as at least one of g, h has degree 1. \square

Given $f \in \mathbb{Q}[x]$ with $\deg(f) > 1$, is it irreducible in $\mathbb{Q}[x]$?

Note: If $f \in \mathbb{Q}[x]$, $f \neq 0$, we can find nonzero $c \in \mathbb{Z}$ such that $cf \in \mathbb{Z}[x]$.

Rational roots of an integer polynomial?

Let $f = a_n x^n + \dots + a_1 x + a_0 \in \mathbb{Z}[x]$ $\deg(f) = n$. We may assume that $a_0 \neq 0$ and $a_n \neq 0$ because $\deg(f) = n$.

Suppose that f has a rational root α . Write $\alpha = \frac{r}{s}$, $s \neq 0$, $s, r \in \mathbb{Z}$, $\gcd(r, s) = 1$.

$f(\alpha) = 0 = a_n \frac{r^n}{s^n} + a_{n-1} \frac{r^{n-1}}{s^{n-1}} + \dots + a_0 \frac{r^0}{s^0} = 0$. Thus, multiply f by s^n and we obtain $a_n r^n s^0 + a_{n-1} r^{n-1} s^1 + \dots + a_0 s^n = 0$. $a_n r^n = -a_{n-1} r^{n-1} s^1 - \dots - a_0 s^n$. s divides the right hand side. Thus, $s | a_n r^n$. As $\gcd(r, s) = 1$, $s | a_n$. Symmetrically, $r | a_0 s^n \implies r | a_0$.

“Here is a deeply stupid algorithm for determining what the rational roots might be.”

Look at all $r \in$ factors of a_0 , the factors of $s \in$ factors of a_n . look at all pairs of r, s with $\gcd(r, s) = 1$

Next: Let $\varphi : R \rightarrow S$ be a ring homomorphism. We can define $\varphi^* : R[x] \rightarrow S[x]$

$$\varphi^* \left(\sum_{i=0}^N r_i x^i \right) = \sum_{i=0}^N \varphi(r_i) x^i$$

Fact: φ^* is a ring homomorphism.

Moreover, if we want it to preserve $\varphi^*(x) = \varphi(x)$ and $\varphi^*(r) = \varphi(r)$ for $r \in R$, then the φ^* is the only such ring homomorphism.

Key point: If $fg = h$ in $R[x]$, $\varphi^*(f)\varphi^*(g) = \varphi^*(h)$ in $S[x]$.

◀ Lecture 33 (2016–04–18)

Class Note

There will be a final exam on Monday, May 9th.

Homework 11 will be due Wednesday April 20th.

Homework 12 will be due Wednesday April 27th.

Homework 13 will not be due.

Example. Show that $\mathbb{Q}[x]/(x^3 - 2x^2 - x + 387)$ is a field.

First off, denote by $p(x)$ the polynomial $x^3 - 2x^2 - x + 387$.

Several steps:

- (1) Since $\mathbb{Q}[x]$ is commutative with $1 \neq 0$, it's enough to show that $I = (p(x))$ is maximal.
- (2) Since $\mathbb{Q}[x]$ is a PID, it's enough to show that $p(x)$ is irreducible in $\mathbb{Q}[x]$.
- (3) Since $p(x)$ is primitive in $\mathbb{Z}[x]$, by Gauss' Lemma, it is sufficient to show that $p(x)$ is irreducible in $\mathbb{Z}[x]$.
- (4) By reducing mod $2\mathbb{Z}$, it's sufficient to show that $\overline{p(x)}$ is irreducible in $(\mathbb{Z}/2\mathbb{Z})[x]$. If we had a factorization $p = ab$ in \mathbb{Z} , we would still have a factorization in $\mathbb{Z}/2\mathbb{Z}$ of $\overline{p} = \overline{a}\overline{b}$. Note that $\overline{p(x)} \equiv x^3 + x + 1$ in $(\mathbb{Z}/2\mathbb{Z})[x]$
- (5) As $\deg(\overline{p}) \leq 3$, It's sufficient to show that \overline{p} has no root in $(\mathbb{Z}/2\mathbb{Z})$. So we try both things in $(\mathbb{Z}/2\mathbb{Z})$. $\overline{p}(0) = \overline{1} \neq 0$ and $\overline{p}(1) = \overline{1} \neq 0$

Hence, $\mathbb{Q}[x]/(p(x))$ is a field. □

Question: What is $\mathbb{Q}[x]/(p(x))$? Typical elements have the form $f(x) + (p(x))$. By the division algorithm, for any $f(x) \in \mathbb{Q}[x]$, we can find $a, b, c \in \mathbb{Q}$ such that $f(x) = ax^2 + bx + c \pmod{p(x)}$

Put $\xi = x + (p(x)) \in \mathbb{Q}[x]/(p(x))$. All elements of $F = \mathbb{Q}[x]/(p(x))$ have the form $a\xi^2 + b\xi + c$.

Claim. $p(\chi) = 0 + (p(x)) \in F$

Pf. $p(x + (p(x))) = p(x) + (p(x)) = 0 + (p(x))$. □

Note now that \mathbb{Q} (the constant polynomials) is a subfield of F . So F is a field extension of \mathbb{Q} . But now F contains a root χ of $p(x)$. The key observation here is that the non-zero elements of F are still invertible.

Example. What is χ^{-1} ?

First step: $\chi(-\chi^2 + 2\chi + 1) = -\chi^3 + 2\chi^2 + \chi = -(2\chi + \chi - 387) + 2\chi^2 + \chi = 387$ Thus,
 $\chi^{-1} \frac{-1}{387} \chi^2 + \frac{2}{387} \chi + \frac{1}{387}$

Example. $\mathbb{C} = \mathbb{R}[x]/(x^2 + 1)$

Lemma 13.37.1 (Wimpy Lemma). *Suppose R is an ID, $p(x), q(x) \in R[x]$ such that $p(x)q(x) = cx^n$ (their product is a monomial). Then, both $p(x)$ and $q(x)$ are both monomials.*

Pf. Let i, j be the indicies of the last non-zero coeffs in p, q respectively. I.e., $p(x) = a_\ell x^\ell + \dots + a_i x^i + 0 + 0 + \dots$ and $q(x) = b_m x^m + \dots + a_j x^j + 0 + 0 + \dots$

Then, $p(x)q(x) = a_\ell b_m x^{\ell+m} + \dots + \underbrace{a_i b_j x^{i+j}}_{\neq 0}$. Thus, $\ell = i$ and $m = j$ □(Lem.)

Theorem 13.38 (Eisenstein Criterion). *Let R be an ID, $P \subseteq R$ a prime ideal.*

If $p(x) = x^n + a_{n-1}x^{n-1} + \dots + a_1x + a_0$ in $R[x]$ with all $a_i \in P$ ($0 \leq i \leq n-1$) and $a_0 \notin P^2$ (i.e., $\nexists r, s \in P$ s.t. $a_0 = rs$). Then $p(x)$ is irreducible in $R[x]$.

Proof. R is an ID, $P \subseteq R$ is a prime ideal. $p(x) = x^n + a_{n-1}x^{n-1} + \dots + a_1x + a_0$. Reduce everything mod P . R/P is an ID. $(R/P)[x]$ is also an ID. $p(x) \equiv x^n \pmod{P}$.

Towards a contradiction, assume $p(x) = f(x)g(x)$ is a proper factorization in $R[x]$. (This implies $\deg(f), \deg(g) < \deg(p)$.)

In $(R/P)[x]$, $x^n = \overline{p(x)} = \overline{f(x)g(x)}$. Thus, by the Wimpy Lemma, both $\overline{f(x)}$ and $\overline{g(x)}$ are monomials in $(R/P)[x]$.

Say $\overline{f(x)} = bx^\ell$ and $\overline{g(x)} = cx^m$ in $(R/P)[x]$.

So $f(x) = b_\ell x^\ell + b_{\ell-1}x^{\ell-1} + \dots + b_0$ and $g(x) = c_mx^m + c_{m-1}x^{m-1} + \dots + c_0$ In particular $b_0 \in P$ and $c_0 \in P$. Thus, $a_0 = b_0c_0 \in P^2$, which is a contradiction. □

Example. Eisenstein for $\mathbb{Z}[x]$:

If $f(x) = x^n + a_{n-1}x^{n-1} + \dots + a_1x + a_0 \in \mathbb{Z}[x]$, if there exists a prime p such that $p|a$ for all $0 \leq i \leq n-1$ and $p^2 \nmid a_0$, then $f(x)$ is irreducible in $\mathbb{Z}[x]$.

14. Field Theory

◀ Lecture 35 (2016–04–20)

Class Note

The midterm 2 average was an 82.

Also, Sylow's theorems will definitely be on the final exam.

Now that we're talking about fields, a lot of this will come from chapter 12/13 in the textbook.

Definition 14.1. If $F \subseteq K$ are both fields (with the same operation), we say that F is a subfield of K , or K is a extension (or field extension) of F .

Note: when $F \subseteq K$, $0_F = 0_K$ and $1_F = 1_K$.

Definition 14.2. A (finite) basis for K over F is a set $B = \{\beta_1, \dots, \beta_n\} \subseteq K$ such that for all $k \in K$, $\exists!$ sequence $f_1, f_2, \dots, f_n \in F$ such that $k = f_1\beta_1 + f_2\beta_2 + \dots + f_n\beta_n$.

Example.

- (1) $\mathbb{R} \subset \mathbb{C}$, a good basis is $\{1, i\}$. Another one is $\{1 + i, 1 - i\}$. (Thus, bases are not unique).
- (2) If F is a field and $p(x) \in F[x]$ is an irreducible polynomial of degree n , then if $k = F[x]/(p(x)) \supseteq F$, then $B = \{1, \alpha, \alpha^2, \dots, \alpha^{n-1}\}$ (just apply the division algorithm)

Note that this is similar to the concept of a basis in linear algebra.

Proposition 14.3. Suppose $F \subseteq K$ and $B = \{\beta_1, \dots, \beta_n\} \subseteq K$. Then B is a basis if and only if:

- (a) $\forall k \in K, \exists f_1, \dots, f_n \in F$ s.t., $k = \sum_{i=1}^n f_i\beta_i$, and
- (b) If $\sum_{i=1}^n f_i\beta_i = 0$ then $f_i = 0$ for $1 \leq i \leq n$.

Proof. The forward direction holds, as there is a unique representation for everything in terms of linear combinations of basis elements (this includes 0).

The backward direction is as follows:

We only need to establish uniqueness. Suppose toward a contradiction that $\exists k \in K$ such that $k = \sum_{i=1}^n f_i\beta_i$ and $k = \sum_{i=1}^n g_i\beta_i$ with not all $f_i = g_i$.

Then $0 = k - k = \sum_{i=1}^n (f_i - g_i)\beta_i$. Since $f_k \neq g_k$ for some k , this contradicts (b). \square

Theorem 14.4. Suppose $F \subseteq K$ are fields, $A = \{\alpha_i\}_{i=1}^m \subseteq K$ and $B = \{\beta_i\}_{i=1}^n \subseteq K$ are both bases for K over F . Then $|A| = |B|$ (i.e., $m = n$).

Lemma 14.4.1 (Switcheroo Lemma). Suppose $F \subseteq K$ are fields. Suppose $B = \{\beta_i\}_{i=1}^n$ is a basis for K over F . Suppose $k \in K$ exists with $k = \sum_{i=1}^n f_i\beta_i$ with $f_i \in F$ for all i .

Now fix any i for which $f_i \neq 0$.

Then, $(B \setminus \{\beta_i\}) \cup \{k\}$ is also a basis for K over F .

Proof. WLOG, assume $i = 1$. We know that $k = f_1\beta_1 \dots f_n\beta_n$. Solving for β_1 gives $f_1\beta_1 = k - \sum_{j=2}^n f_j\beta_j$. As $f_1 \neq 0$, we can divide by it. $\beta_1 = \frac{1}{f_1}k - \sum_{j=2}^n \frac{f_j}{f_1}\beta_j$.

Now we show that $B' = \{k, \beta_2, \dots, \beta_n\}$ is a basis for K over F .

Use proposition 14.3.

(a) $\forall \ell \in K, \exists h_1, \dots, h_n \in F$ such that $\ell = hk + h_2\beta_2 + \dots + h_n\beta_n$

(b) $0 = h_1k + h_2\beta_2 + \dots + h_n\beta_n$ then $h_1 = f_2 = \dots = h_n = 0$. Use that 0 has a unique representation in the β s. (Left to the reader)

□(Lem.)

Now we prove theorem 14.4.

Proof. We follow an algorithm described as follows:

We have m boxes, box i contains α_i . There is a “bank,” which contains all the β s.

We halt when every box has a β in it, or the bank is empty.

While we have not halted, we use the Switcheroo Lemma to remove some β_i from the bank and replace some α_j with it.

However, we need to be assured that $\beta_k = \sum_{\text{boxes with } \alpha} f_i\alpha_i + \sum_{j \in \text{boxes with } \beta} g_j\beta_{i_j}$

Claim. Some f_i is non-zero.

Otherwise, B is not a basis.

Thus, the Switcheroo Lemma means that at each step, we still have a basis in the boxes.

After we halt, there are two possible states.

Case 1 (The β s in the boxes (B') are a subset of B):

Pf of case 1. Towards a contradiction, suppose $\beta \in B \setminus B'$. The unique representation of β in B is β . But that representation isn't in B' . Thus, B' is not a basis. It follows that no such β exists, so $B = B'$. □

Case 2 (The bank is empty at the end, so the items in the boxes ($B'' \supseteq B$))

Pf of case 2. If $n \neq m$, there is some $\alpha \in B'' \setminus B$. Since B is a basis, we know $\alpha = f_1\beta_1 + \dots + f_n\beta_n$. This is therefore another representation of α in B'' , contradicting uniqueness. □

□

◀ Lecture 36 (2016–04–22)

Class Note

Homework 12 is now due Friday, April 29th

Let $F \subseteq K$ be fields.

Definition 14.5. If $F \subseteq K$ admits a basis of cardinality $n < \infty$, the extension has degree n , written $[K : F] = n$

Definition 14.6. If $F \subseteq K$ admits a finite basis, we say that K is a finite-degree extension of F .

Example.

- $[\mathbb{C} : \mathbb{R}] = 2$ as $\{1, i\}$ is a basis
- $[\mathbb{R} : \mathbb{Q}]$ is not finite, and it apparently has only horrible bases.

More generally, if $p(x) \in F[x]$ is irreducible, and $\deg(p) = n$, then

$$[F[x]/(p(x)) : F] = n$$

Remark. (From homework): If F is a finite field, (say $|F| = q$) and $F \subseteq K$, with $[K : F] = n$ then $|K| = q^n$.

Proposition 14.7. *If $F \subseteq K$ are fields and $[K : F] = 1$ then $F = K$.*

Proof. Fix a basis $B = \{\beta\}$ for K over F . I.e., $\forall k \in K (\exists! f \in F (k = F\beta))$. In particular, $\exists f \in F$ such that $f\beta = 1 = \beta^{-1}\beta$. Since $\beta \neq 0$ and fields are integral domains, we conclude $\beta^{-1} = f \in F$. Thus, $\beta \in F$, so $K \subseteq F$. \square

Proposition 14.8. *Suppose $[K : F] = m$, $n > m$, and $\gamma_1, \dots, \gamma_n$ is a sequence of elements of K . Then, we may take $\ell < n$ and $f_1, \dots, f_{\ell-1} \in F$ such that $\gamma_\ell = \sum_{i=1}^{\ell-1} f_i \gamma_i$.*

Proof. Fix a basis $B = \{\beta_1, \dots, \beta_m\}$ for K over F .

We apply the algorithm from theorem 14.4 with B in the boxes, and γ_i in the bank, replacing a β with γ_i for the least i left in the bank, halting when we can no longer replace any β with γ_i .

At this last stage, we know that

$$\gamma_i = \sum_{\text{box } j \text{ with } \beta} g_j \beta_j + \sum_{\text{box } k \text{ with } \gamma} f_k \gamma_{z_k}$$

If some $g_i \neq 0$ then use the Switcheroo Lemma. Otherwise, $g_i = 0$, then we have $\gamma_i = \sum_{j < i} f_j \gamma_j$ \square

Corollary 14.8.1. *Suppose $[K : F] = n$. Then for all $\theta \in K$ there is a nonzero polynomial $p(x) \in F[x]$ such that $p(\theta) = 0$ in K .*

Proof. Consider the sequence $1, \theta, \theta^2, \dots, \theta^n$ of length $n+1 > n = [K : F]$. By proposition 14.8, $\exists \ell \leq n$ and $f_i \in F$ such that $\theta^\ell = \sum_{i=0}^{\ell-1} f_i \theta^i$. Choose $p(x) \in F[x]$ with $p(x) = x^\ell - \sum_{i=0}^{\ell-1} f_i x^i$. $p(\theta) = 0$. \square

Definition 14.9. In fields $F \subseteq K$, we say $\theta \in K$ is algebraic over F if it is the root (in K) of some nonzero polynomial $p(x) \in F[x]$.

Example.

- In $\mathbb{C} \supset \mathbb{Q}$, i is algebraic, since it is the root of $x^2 + 1 = f(x) \in \mathbb{Q}[x]$.
- In $\mathbb{R} \supset \mathbb{Q}$, π is *not* algebraic, but it's a pain to prove.
- In $\mathbb{R} \supset \mathbb{Q}$, $3^{1/3} + 3^{2/3}$ is algebraic.

Put $\alpha = 3^{1/3}$, so $\alpha^3 = 3$. Put $\theta = \alpha^2 + \alpha$. Grind through $1, \theta, \theta^2$ until we can express one in terms of the other. We get $\theta^3 = \theta^2 \theta = 9\alpha^2 + 9\alpha + 12 = 9\theta + 12$, hence, θ is a root of $x^3 - 9x - 12 \in \mathbb{Q}[x]$.

Proposition 14.10. *Suppose $F \subseteq K$ and $\theta \in K$ is algebraic over F . Then there exists a unique monic (nonzero) irreducible polynomial $m(x) \in F[x]$ with $m(\theta) = 0$ (in K). Moreover, $\forall p(x) \in F[x]$, if $p(\theta) = 0$ in K , then $m(x) | p(x)$ in $F[x]$.*

Definition 14.11. $m(x)$ is called the minimal polynomial of θ in $F[x]$.

Proof. Define $\text{ev}_\theta : F[x] \rightarrow K, p(x) \mapsto p(\theta)$.

$I = \text{Ker}(\text{ev}_\theta) \subseteq F[x]$ is an ideal, and $m(x)$ is the unique monic polynomial such that $I = (m)$. \square

◀ Lecture 37 (2016–04–25)

Definition 14.12. If $F \subseteq K$ are fields, and $\theta \in K$, let $F(\theta)$ be the smallest subfield of K with $F \subseteq \theta$ and $\theta \in F(\theta)$.

Formally, $F(\theta) = \bigcap_{\substack{L \subseteq K \text{ a field} \\ F \subseteq L \\ \theta \in L}} L$.

You're in F , some alien who sees more dimensions and stuff sees K . It gives you an element θ from K as a gift. If θ is algebraic over F , then you've gained nothing \odot .

Proposition 14.13. Suppose $F \subseteq K$ are fields, $\theta \in K$ is algebraic over F . Then $F(\theta) \cong F[x]/(m(x))$ where $m(x) \in F[x]$ is the minimal polynomial of θ .

Proof. Consider the map $\varphi : F[x] \rightarrow K, \varphi(p(x)) = p(\theta)$ (i.e., $\varphi = \text{eval}_\theta$). We know that $\text{Ker}(\varphi) = (m(x))$.

By the first isomorphism theorem, we know $\text{Im}(\varphi) \cong F[x]/(m(x))$. It only remains to show that $\text{Im}(\varphi) = F(\theta)$.

Claim (1). $F(\theta) \subseteq \text{Im}(\varphi)$. Need to check

- (1) $\text{Im}(\varphi) \subseteq K$ ✓
(It's a field, since it's $\cong F[x]/(m(x))$)
- (2) $F \subseteq \text{Im}(\varphi)$, since $\forall x \in F \varphi(x) = x$
- (3) $\theta \in \text{Im}(\varphi)$. $\varphi(x) = \theta$.

Hence $F(\theta) \subseteq \text{Im}(\varphi)$

Claim (2). Fix $k \in \text{Im}(\varphi)$ So $\exists f_0, \dots, f_n \in F$ such that $k = f_n \theta^n + f_{n-1} \theta^{n-1} + \dots + f_1 \theta + f_0$. So $k \in F(\theta)$.

$\square(\text{Prop.})$

Example. Consider $\mathbb{Q} \subseteq \mathbb{C}$. Put $\theta_1 = \sqrt[3]{2}, \theta_2 = (\frac{-1}{2} + \frac{\sqrt{3}}{2}i)\sqrt[3]{2} = \sqrt[3]{2}e^{i2\pi/3}$

$\mathbb{Q}(\theta_1) \neq \mathbb{Q}(\theta_2)$ since $\mathbb{Q}(\theta_1) \subset \mathbb{R}$ but $\mathbb{Q}(\theta_2) \not\subset \mathbb{R}$. But, $\mathbb{Q}(\theta_1) \cong \mathbb{Q}(\theta_2)$ as fields. θ_1, θ_2 both have minimal polynomial $x^3 - 2$.

Iterated Extensions

Theorem 14.14. Suppose $F \subseteq K \subseteq L$ are fields with $[K : F] = m < \infty$ and $[L : K] = n < \infty$. Then $[L : F] = [L : K][K : F] = mn$.

Proof. In the finite case, if $|F| = q < \infty$ then $|K| = q^m$ and $|L| = |K|^n = (q^m)^n = q^{mn} = |F|^{mn}$

Fix a basis $B = \{\beta_1, \dots, \beta_m\}$ for K over F and $C = \{\gamma_1, \dots, \gamma_n\}$ for L over K .

Put $A = \{\beta_i \gamma_j, : i \in [m], j \in [n]\}$

Claim. A is a basis for L over F .

Pf of Claim. We need to show that $\forall \ell \in L$, there is a unique sequence $(f_{i,j})_{\substack{i \in [m] \\ j \in [m]}}$ of elements from F such that

$$\ell = \sum_{\substack{i \in [m] \\ j \in [n]}} f_{i,j} \beta_i \gamma_j = \sum_{j \in [n]} \gamma_j \underbrace{\left(\sum_{i \in [m]} f_{i,j} \beta_i \right)}_{\text{denote by } k_j \in K}$$

So, $\ell = \sum_{j \in [n]} k_j \gamma_j$.

There exists a unique k_1, \dots, k_n making this true, since C is a basis for L over K . Thus, A is a basis for L over F , as desired. $\square(\text{Claim})$

$\square(\text{Thm.})$

Definition 14.15. Let $F \subseteq K$ be fields, $\theta_1, \theta_2 \in K$. Let $F(\theta_1, \theta_2)$ be the smallest subfield of K containing F, θ_1, θ_2 . So, $F(\theta_1, \theta_2) = (F(\theta_1))(\theta_2)$.

Corollary 14.15.1. If θ_1 and θ_2 are algebraic,

$$[F(\theta_1, \theta_2) : F] = \underbrace{[F(\theta_1, \theta_2) : F(\theta_1)]}_{\substack{\text{deg of min'l poly} \\ \text{of } \theta_2 \text{ in } F(\theta_1)}} \underbrace{[F(\theta_1) : F]}_{\substack{\text{deg of min'l poly} \\ \text{of } \theta_1 \text{ in } F}}$$

Example. $[\mathbb{Q}(\theta_1, \theta_2) : \mathbb{Q}] = 6$ Note $\sqrt{3}i \in \mathbb{Q}(\theta_1, \theta_2)$.

$\frac{\theta_2}{\theta_1} = \frac{-1}{2} + \frac{\sqrt{3}}{2}i$. Has minimal polynomial $x^2 + 3$

$\mathbb{Q} \subseteq \mathbb{Q}(\sqrt{3}i) \subseteq \mathbb{Q}(\theta_1, \theta_2)$. Hence $[\mathbb{Q}(\theta_1, \theta_2) : \mathbb{Q}]$ is even.

To compute the 6, we need $[\mathbb{Q}(\theta_1, \theta_2) : \mathbb{Q}(\theta_1)] = 2$

$$x^3 - 2 = (x - \theta_1)(x^2 + \theta_1 x + \theta_1^2)$$

◀ Lecture 38 (2016–04–27)

Tips and tricks for computing degrees of field extensions.

Recall if $F \subseteq K$ are both fields, $\theta \in K$ is algebraic iff $[F(\theta) : F]$ is finite, which is equivalent to θ being the root of some polynomial in $F[x]$

Moreover, $[F(\theta) : F] = \deg(m_\theta(x))$ where $m_\theta(x) \in F[x]$ is the minimal polynomial of θ in $F[x]$.

Work in the rationals $\mathbb{Q}, \theta \in \mathbb{C}$. What's the degree of θ over \mathbb{Q}

One strategy: Compute $m_\theta(x)$ by checking powers of θ , and report the degree of $m_\theta(x)$.

Example. $\theta = \frac{1}{2 + \sqrt[3]{6}}$ What is $[\mathbb{Q}(\theta) : \mathbb{Q}]$?

Sneakier approach:

Claim. $\mathbb{Q}(\theta) = \mathbb{Q}(\sqrt[3]{6})$

Proof. $\mathbb{Q} \subseteq \mathbb{Q}(\theta)$ and $\mathbb{Q} \subseteq \mathbb{Q}(\sqrt[3]{6})$

Note that $\theta \in \mathbb{Q}(\sqrt[3]{6})$ Hence $\mathbb{Q}(\theta) \subseteq \mathbb{Q}(\sqrt[3]{6})$

Analogously $\sqrt[3]{6} = \frac{1}{\theta} - 2 \in \mathbb{Q}(\theta)$. Thus, $\mathbb{Q}(\sqrt[3]{6}) \subseteq \mathbb{Q}(\theta)$. \square

Thus, since $\sqrt[3]{6}$ has minimal polynomial $x^3 - 6$, both θ and $\sqrt[3]{6}$ have degree 3.

Example.

$$\theta = \frac{\sqrt[3]{2} - \sqrt[3]{8}}{1 + \sqrt[3]{16} + \sqrt[3]{4}}$$

Look at $[\mathbb{Q}(\sqrt[3]{2}) : \mathbb{Q}] = 3$

We know that $\theta \in \mathbb{Q}(\sqrt[7]{2})$.

Hence $\mathbb{Q} \subseteq \mathbb{Q}(\theta) \subseteq \mathbb{Q}(\sqrt[7]{2})$ and so $[\mathbb{Q}(\theta) : \mathbb{Q}]$ divides $[\mathbb{Q}(\sqrt[7]{2}) : \mathbb{Q}] = 7$

We claim it isn't 7.

Toward a contradiction, if $[\mathbb{Q}(\theta) : \mathbb{Q}] = 1$ Then $\mathbb{Q}(\theta) = \mathbb{Q}$, so θ is rational. Say $\theta = q \in \mathbb{Q}$

Put $y = \sqrt[7]{2}$ $q = \theta = \frac{y-y^3}{1+y^4+y^2}$, so $q(1+y^4+y^2) = y-y^3$, or $qy^4+y^3+qy^2-y+q=0$. It follows that $\sqrt[7]{2}$ is a root of a degree 4 polynomial, but x^7-2 is minimal, RAA.

Straight Edge and Compass Constructions

Idea: Start with two “marked” points on a plane.

Allowable Moves:

- Draw a straight line between two marked points
- Draw a circle centered at a marked point whose radius is the distance between two (possibly unrelated) marked points
- Mark a point that is the intersection of two (disjoint) drawn so far.

We declare the starting points to be $(0,0)$ and $(1,0)$

More formally, a “construction” is a sequence $\{(0,0), (1,0)\} = P_0 \subseteq P_1 \subseteq \dots \subseteq P_n$. Each P_i is a finite set of points in the plane.

$P_{i+1} = P_i \cup Q_i$, where Q_i is a the intersection of two distinct lines/circles built out of P_i .

Let's say a real number $r \in \mathbb{R}$ is constructable if it appears as either the x or y -coordinate of some point in P_n , for some construction.

We know that all $z \in \mathbb{Z}$ is constructable, all $q \in \mathbb{Q}$ is constructable, and all $\{\sqrt{q} : q \in \mathbb{Q}\}$ are all constructable.

Next time:

Theorem 14.16. Suppose $P_0 \subseteq P_1 \subseteq \dots \subseteq P_n$ is a construction.

Then there is a field K with $\mathbb{Q} \subseteq K \subseteq \mathbb{R}$ such that $\{x \text{ and } y \text{ coordinates of } P_n\} \subseteq K$ and $[K : \mathbb{Q}] = 2^\ell$ for some $\ell \in \mathbb{N}$.

Why is this useful?

Proposition 14.17. $\sqrt[3]{2}$ is not constructable.

Proof. Suppose it were, fix a construction $P_0 \subseteq \dots \subseteq P_n$ with $(\sqrt[3]{2}, y) \in P_n$.

Fix also K as in the theorem such that $\sqrt[3]{2} \in K$. Hence, $\mathbb{Q}(\sqrt[3]{2}) \subseteq K$ So $\mathbb{Q} \subseteq \mathbb{Q}(\sqrt[3]{2}) \subseteq K$.

Hence $\underbrace{[K : \mathbb{Q}]}_{=2^\ell} = [K : \mathbb{Q}(\sqrt[3]{2})] \underbrace{[\mathbb{Q}(\sqrt[3]{2}) : \mathbb{Q}]}_{=3}$ □

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